School of Environment and Life Sciences

MSc Thesis

ENERGY SECURITY IN ASIA - HIMALAYAN HYDROPOWER

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Abstract

This thesis explores actual and potential feasibility of investment in hydropower in the Himalayan region and China. Hydropower's carbon free and sustainable image has come under threat thanks to increasing concerns over climate change, population growth, and energy demand. Existing implications and evolving externalities are increasingly threatening the feasibility of current and future developments. The Himalayas natural water resources and high gradients make it the ideal location for power to be sourced through hydropower. The scale of the Himalayas untapped hydropower potential encourages the argument that further investment in the resource would be economically feasible. Analysis of former patterns and relationships associated with Himalayan hydropower takes place and evolving implications that threaten the productivity of future hydropower performance are applied throughout. River runoff is reducing in the Himalayas, threatening to decrease the efficiency of hydropower operation. Reduction in water availability exacerbates water security concerns in the Himalayas. Water and energy security issues are also threatened by exponential increases in the region's population. Population growth is the greatest catalyst behind the sustainability issues that threaten Asia's economic growth. There are huge pressures to sustainably accommodate this growing population through renewable sources. The scale of increased demand for energy however is likely to become more significantly met by thermal sources as the productivity of hydropower is set to reduce without successful mitigation attempts. Despite environmental awareness increasing throughout Asia and a cooling economic climate in China, soaring energy needs are outpacing the expansion of climate friendly renewable power.

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Declaration

I certify that this master's thesis consists of my original work. All quotations from published and unpublished sources are acknowledged as such in the text. Material derived from other sources is also indicated.

The total number of words in the main text is **31,412** (excluding references)

Name: Matthew Harry Deane

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1. Introduction

1.1. Background

Energy security is recognised as a country's ability to secure sustainable energy supplies for itself at realistic prices (Energy Global, 2011). Energy supply is particularly acute in Asia whereby energy sectors must typically grow by 2-3% over the GDP growth rate to simply sustain the economy (Sankar *et al.* 2000). To meet growing aspirations of people and economies, Asia is under immense social and political pressure to secure reliable, sustainable, and reasonably priced energy supplies (USEA, 2012). There are growing concerns of the growing supply-demand imbalance being experienced throughout Asia. Decades of globalisation, strong economic growth, increasing populations, and urbanisation have fuelled an exponential rise in energy demand (Ogutcu, 2002). There has not however been any matching rise in production. Globalisation has encouraged Asia's contribution to the world economy enormously over recent decades as Asian economies have become more integrated with the developed world (Camdessus, 1997). Whilst fuelling economic growth, globalisation impacts have however contributed toward economic and energy disparity throughout Asia, whereby inequality is realised through unfair distribution (Francis *et al.* 2010).

Emerging economies in Asia are now entering their most energy intensive phase of development. In line with rising living standards, countries such as China and India are increasing their consumption of energy for industrialisation, infrastructure construction, transportation and development (Lehmann *et al.* 2013). It is estimated that if current trends continue, by 2030, half of future energy demand will come from China and India, both of which are currently net importers. It is crucial therefore that Asia secures sustainable access to energy sources to meet the aspirations and demands of their growing middle income earners (Sankar *et al.* 2013). Lehmann *et al* (2013), argue that energy represents the 'Achilles Heel' of Asia's potential economic development.

To help mitigate energy concerns, the South Asia Regional Initiative for Energy (SARI/Energy) was launched in 2000 to promote energy security through increased trade, investment, and access to clean sources of power (USEA, 2012). A significant proportion of Asian people has either no access to electricity at all or is undersupplied. Shortages of power seriously hamper Asia's industrial and socio-economic growth

(Sankar *et al.* 2000). In Asia there has been a sustained shift from traditional to commercial sources of energy over the past two decades.

Asia possesses significant indigenous hydropower resources (IEA, 2014). These resources however have not been distributed evenly throughout the region, leading to a distinct lack of development. As a result, Asia relies significantly on imported commercial fuels (Noronha *et al.* 2013). This is a particular drain on less developed economies that have limited accessible capital to continue such expenditure without inward investment from elsewhere (Pomeranz, 2013).

Diversifying energy supply and reducing expenditure on imports is crucial in light of energy security concerns. Hydropower is the most prevalent source of renewable energy in the world (Kalair, 2012), and South Asia has the largest untapped potential of this renewable resource (World Bank, 2013). The high specific runoff of Himalayan Rivers represents Asia's key driving force behind the potential for future energy security within riparian nations (Rahaman, 2012). Hydropower constitutes 21% of the world's electricity generating capacity (Knive, 2011). The theoretical potential of world hydropower is about 4 times greater than the amount that has been tapped. Tapped potential however will never reach the theoretical maximum level due to ever increasing environmental concern and political constraint (Knive, 2011).

The feasibility of hydropower in the Himalayan region is ultimately threatened by three main externalities. These include glacial melt water production, monsoon precipitation, and reservoir sedimentation. Laghari (2013) explains how climate change represents the greatest threat to the economic feasibility of hydropower in Asia. Seasonal melt waters serve as an increasing source of power for a growing number of hydroelectric dams along Himalayan Rivers (Harrison *et al.* 2012). The stability of this natural resource is however becoming increasingly endangered thanks to changing hydro-meteorological conditions and the impending realisation of the deglaciation discharge dividend (Collins, 2008).

Harnessing the immense untapped hydropower potential in the Himalayas has opened avenues for poverty alleviation, whilst making a substantial contribution to the national economies (World Bank, 2013). Trans-boundary trade is a way of achieving unmet demand for electricity (Knive, 2011). Hydropower provides an opportunity for some countries to reduce reliance on external energy sources. Nepal for example, which has only developed 2% of its technically feasible hydropower capacity, is a net importer of electricity to meet shortages of 0.61 TWh annually (Knive, 2011). A more conscientious effort to utilise unharnessed capacity would enable Nepal to generate more revenue through increasing sales of electricity to India. Increased energy interdependence improves relationships between countries and decreases risks of power shortage. Energy security helps to improve investment climates, fuelling economic growth.

1.2. Research focus

The purpose of this thesis is to analyse the feasibility of increased investment into hydropower in the Himalayan Region of Asia. Utilising a greater percentage of the untapped potential that lies within the Himalayas presents economic opportunities for Asia that should not be overlooked. An analysis of the externalities that act as obstacles to developing this feasibility has therefore been carried out. Externalities that cover the economic implications of dam construction, the political and environmental constraints that slow progress, and the geopolitical relationships required to initiate economic growth that demands such an intensive consumption of energy have been analysed.

What are the implications of climate change, population growth, and reservoir sedimentation on the potential feasibility of increased investment into hydropower in the Himalayan region of Asia?

In answering this question, theories relating to the relationship between climate change, glacial melt, river discharge, and hydropower generation are discussed in detail through the analysis of existing stations. More political aspects of hydropower development are examined with particular focus on the transboundary nature of Himalayan rivers, examples of water sharing agreements, and the extra environmental pressures being caused by exponential population growth. The growing risk to water storage capacity is also considered with emphasis on the sedimentation of large reservoirs and its impact on water security, local irrigation, and hydroelectric power generation. Finally, to understand hydropower's potential further to catalyse economic development, its impacts are considered alongside well documented economic growth models.

1.3. Research aims

- To analyse the potential contributions of hydropower toward future economic growth in South Asia and South West China.
- To examine environmental concerns associated with greater investment into Hydropower.
- To assess geopolitical obstacles that impede the feasibility of hydropower development.

- To analyse effects of reservoir sedimentation in the Himalayas and its effects and implications for future hydroelectric productivity and water security.
- To examine how hydropower development has evolved through time in reaction to changes in political attitudes and climate change.

1.4. Importance of this research

The importance of this research relates to analysing current environmental and political implications associated with hydropower in the Himalayas and applying this knowledge when considering the potential future increased development of the power source. Trends and patterns in existing data are analysed to make educated predictions on the future suitability of the Himalayas as a location for increased hydropower development.

It is important to firstly discuss how the topic has emerged from the literature. There is already abundant literature concerning the geopolitical issues of the region that threaten to slow the development of hydropower. Issues concerning trans-boundary river systems, the differing economic and political contexts of riparian nations, water sharing agreements, and concerns over water, food, and energy security are discussed plentifully.

Despite being recognised as a real hazard to hydropower, there does however appear to be a short fall in literature that discusses the scale of the impact that climate change is having on hydroelectric generation in the Himalayas. Climate change and hydropower are discussed as individual issues abundantly, however overlapping and intersecting research between these topics lacks detail.

There also seems to be an insufficient understanding of reservoir sedimentation and its potential threat for future water and energy security. McCully (2008) explains how despite more than six decades of research, sedimentation is still the most serious technical problem faced by dam operation.

Understanding the relationship between climate change and its impacts over river discharge is essential if future projects along Himalayan rivers are to be developed sustainably. Knowledge sourced from the analysis of Himalayan rivers through time could be used to aid future hydroelectric projects. This is because the specifics of current developments are usually based on the assumption that climatic conditions have and continue to remain stationary. The economic feasibility of hydropower projects also rests on the efficiency of production efficiency over the long term. This is because the initial costs of construction are so high, making calculating the pay-back period on a project crucial. As a result, accurate forecasts need to be developed concerning future river discharge and consequent generating potential.

All reservoirs lose water storage capacity to sedimentation, although rates of loss vary widely. Sedimentation simply reduces the efficiency of dam operation, extending the payback period for each project. Understanding the patterns and rates of sedimentation in individual reservoirs will help improve the feasibility of future projects. Such information will also aid the successful implementation of mitigation strategies that will help prevent dams from becoming rendered uneconomic. Future costs of repairing turbines and intakes could also be reduced if the build-up of sediment is controlled. Maintenance time as a result would have less impact on generation potential.

The relationship between hydropower, population growth, and GDP is significant. It is important to understand how each condition affects another and whether one has to be in place before another can develop. For example, does a strong economy have to be in place before investment into hydropower can occur or must hydropower already be developed before economic growth can be realised? The relationship between these factors is crucial in considering the conditions needed for the development of a region.

2. Background

Energy security and water security are fundamental to development (World Bank, 2013). Both factors however represent contentious issues with respect to Asia's economic growth. South Asia is one of the most prosperous regions in the world in terms of water; however population growth, poverty, and political conflicts are restricting the regions ability to use water efficiently (Dasgupta *et al.* 2013).

New academic research suggests that India, Nepal, Bhutan, and Pakistan are involved in a huge 'water grab' in the Himalayas as they seek new sources of electricity to power their economies (Vidal, 2013; Dasgupta *et al.* 2013; Daly, 2013; and others). The World Bank believes that appropriate multipurpose hydropower development can bring significant benefits. These include access to electricity, diversified energy options, managing water scarcity, and supporting water dependent activities (World Bank, 2013). Considering the untapped potential within developing nations, failure to include hydropower in development planning for both water and energy security has risks and costs that cannot be overlooked (Jeuland *et al.* 2013).

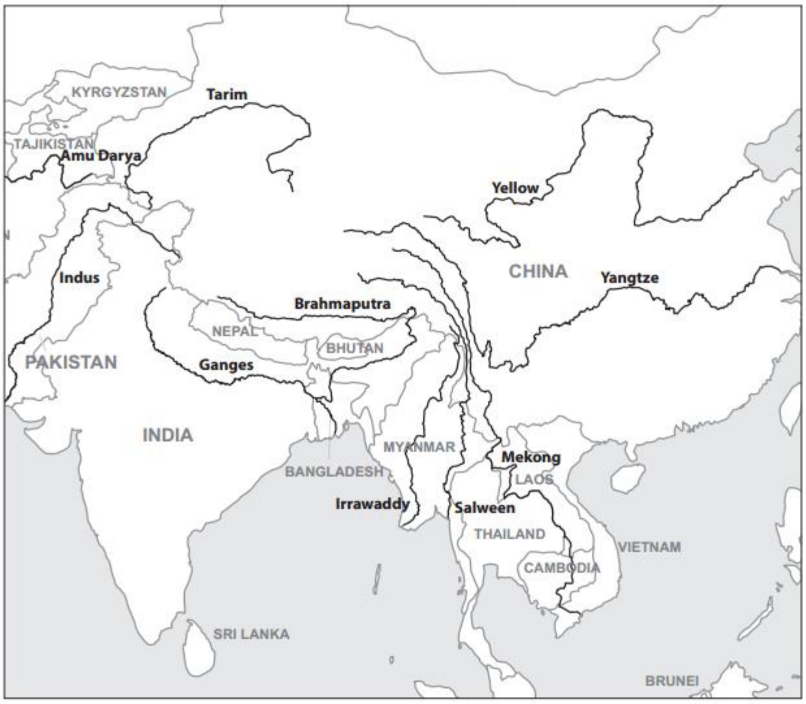


Figure 1: Ten of South Asia's longest and largest rivers (Pomeranz, 2013).

Hydroelectricity is the most prevalent economic source of white energy (Kalair, 2012). The Himalayas are an ideal location for the development of hydropower, thanks to their mountainous and fresh water properties. The region is often acknowledged as being the third pole, with it possessing the largest reserve of fresh water outside of the Arctic and

Antarctic (Bahadur, 1993). Nations within South Asia including Nepal, Bhutan, India, and Pakistan are blessed with the potential to develop hydropower on an enormous scale, providing capital is accessible (Pomeranz, 2013). Hydropower is often driven by a countries desire to reduce its reliance on fossil fuels and diversify its energy sources (Knive, 2011). For lesser developed countries however it can also be used to stimulate economic growth, mitigate matters of water security and relieve poverty (Hangzo, 2012).

The countries mentioned previously have plans for more than 400 hydro dams, which if built, could together provide more than 160’000MW of electricity (Vidal, 2013). In addition to this China have plans to build more than 100 dams to generate a similar amount of power. These dams are to be built on rivers such as those shown in figure 1. Figure 1 shows that ten of the region’s largest and longest rivers originate in the Himalayas (Pomeranz, 2013). These rivers help provide water, food, and energy for nearly 4 billion people across China and South Asia (Pomeranz, 2013). Depletion and diversion of these trans-border resources to meet growing industrial, agricultural, and urban demands however have the potential to trigger far reaching economic, social, and environmental challenges (Dharmadhikary, 2008).

Due to the trans-boundary nature of the water resources in South Asia, few doubt that these problems have a geopolitical dimension. This concern is provoked further by the consequences of climate change and the quickening pace of Chinas dam construction on trans-boundary rivers (Daly, 2013). Under these circumstances it is no wonder that experts are questioning whether South Asia has in place bilateral and multilateral frameworks adequate to the task of managing increasing water and energy security concerns (Wirsing, 2013).

Pomeranz (2013) explains how sustainable management of Himalayan water is restricted by the lack of comprehensive and effective regional frameworks for cooperation. China which controls the headwaters of these rivers for example, has an enormous need for Himalayan water to satisfy economic and energy demands (Vidal, 2013). It has little incentive however in participating in formal water sharing agreements with its riparian neighbours (Turner *et al.* 2013).

Collaboration in South Asia is frequently frustrated by competing national interests, economic priorities, political disputes, and weak regional organisations (Pomeranz, 2013). The environmental impacts of manmade diversion projects and unsustainable freshwater usage are also threatening. Chinas upstream advantage, its engineering capacity and its financial capabilities help ensure relative control over its water future (Daly, 2013). Weaker riparian nations who struggle with high population densities, high poverty levels, energy security issues, and a lack of economic prospects, are however likely to be overpowered in their attempts for economic prosperity (Hangzo, 2012). Atsushi (2007) explains how weaker parties are anticipated to struggle in getting their interests considered.

The broad field of this review relates to the implications associated with the development of Himalayan hydropower. Climate change and population growth are both considered with respect to both water and energy security. The trans-boundary nature of Himalayan Rivers is also reviewed with reference to the scarcity of water sharing agreements between nations and the ensuing political conflicts. The efficiency and effectiveness of current projects is assessed with particular focus on sedimentation and water storage losses. Finally the economic and environmental potential of such hydropower is analysed with reference of economic growth models.

2.1. Current energy security concerns

South Asia currently faces endemic shortages of electricity that threaten its industrial and socioeconomic growth (Sankar *et al.* 2013). Within the region there is currently a shift occurring from traditional to commercial sources of fuel (Knive, 2011). The shift is being led by India and Pakistan, where traditional fuels now contribute towards only 30% of demand (Koch, 2012).

Each country within South Asia is trying to evolve its own strategy to address the issue of energy security. There is now a growing realisation of the need to address energy security from a regional perspective (USEA, 2012). A regional approach facilitates a more comprehensive, cost effective, and sustainable set of solutions to the challenges of energy security (Sankar *et al.* 2013). This is where hydropower appears to complement South Asia's drive toward energy independence.

Currently South Asia imports most of its oil from the Middle East, a region plagued by security concerns and political risk (Chellaney, 2012). Diversifying the sourcing of fuels will help mitigate some of the risks associated with an overdependence on crude and petroleum products from the Middle East. Increasing foreign dependency is becoming a growing concern in South Asia (McMillan, 2008). Energy trade however must be a part of the solution to South Asia's continued development, as South Asian countries don't possess the entire range of energy resources needed to meet its development objectives

(USEA, 2012). McMillan (2008) however explains that South Asian countries face a stark choice between rapid economic development and energy self-sufficiency. Both can't be achieved simultaneously. To be put more simply, energy security cannot be fully achieved if energy independence hasn't been reached.

Regional trade in energy is practically non-existent in South Asia. Longstanding disputes, and mistrust between countries within the region have blocked even modest efforts to encourage regional energy trade (Knive, 2011). This situation is extremely disappointing especially when understanding the potential opportunities for these countries to capitalise on their trans-boundary energy resources for mutual benefit (Koch, 2012). Sankar *et al.* (2013) explains that to effectively take control of the energy security concerns within South Asia, an energy sector master plan must be established, promoting indigenous hydropower resource development. He also argues that this plan must emphasize joint development mechanisms aimed at maximising investments in shared energy infrastructure and resource development (Sankar *et al.* 2013).

Hydropower provides an excellent opportunity for energy trade within the region to bridge the demand-supply gap (McMillan, 2008). It is strongly believed that a greater development in hydropower would bring reductions in investment requirements, lower transmission losses, improve reserve margins, and enhance the reliability of supply in South Asia (Sankar *et al.* 2013). Measuring the feasibility of such an investment however is far more challenging to calculate as a number of externalities threaten its economic impact.

2.2. Climate change and hydropower

Changes in atmospheric concentrations of 'greenhouse gases' as a partial result of anthropogenic activity is predicted to cause climate change (Harrison *et al.* 2012). The current scientific consensus predicts that under current rates of economic and population growth global mean temperatures will rise by 3°C by the end of this century (IPCC, 1998). This is expected to be accompanied by a 15% increase in global precipitation levels (IPCC, 1998). Changes are however likely to be accentuated within more hostile and alpine environments as they are more vulnerable to hydro meteorological change (Roy, 2010).

The South Asian Monsoon system largely defines the climate and hydrology of many catchment systems surrounding the Himalayas (Jeuland *et al.* 2013). The monsoon sweeps up both coasts of the Indian sub-continent until it is blocked by the Himalaya mountain range (Matthew, 2013). The monsoon delivers 80% of annual rainfall in June-August (Dharmadhikary, 2008). In correspondence of this, river flows in the Ganges basin for example rise from very low levels in May to a sharp peak in July to October, as shown in figure 2 (Jeuland *et al.* 2013).

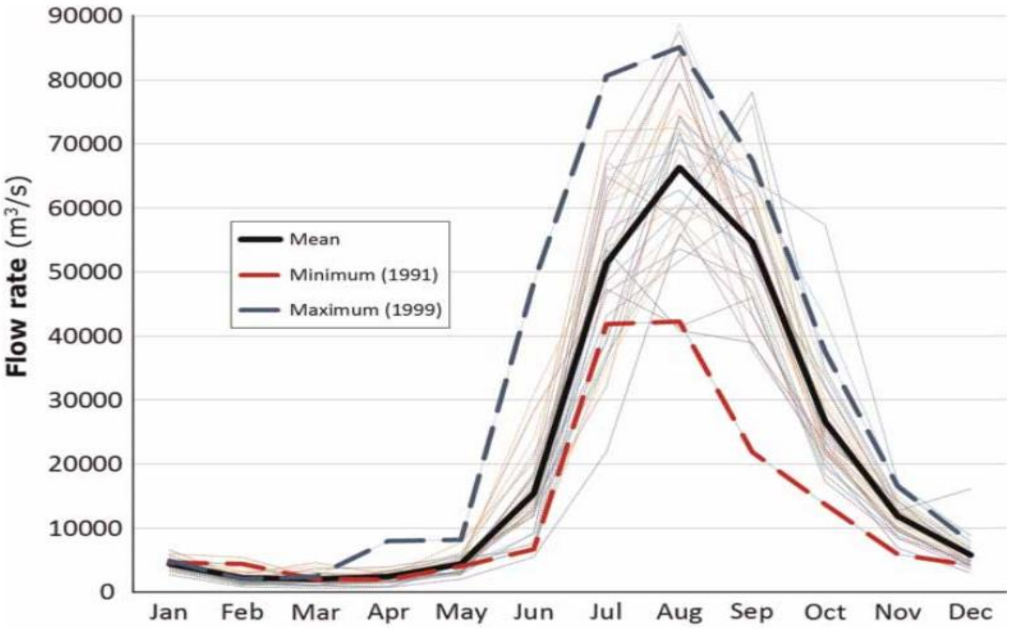


Figure 2: Historical flows at Farakka (India-Bangladesh border), flows from individual years are shown by thin lines (Jeuland *et al.* 2013).

Figure 2 shows that base flows in the river, net of upstream abstractions in India and Nepal are very modest (Jeuland *et al.* 2013). Flows at Farakka from January to May comprise just 6% of total annual flow. Climate and hydrological variability in the Himalayas is also extremely high (Laghari, 2013). This is indicated by the inconsistency of the time series flows shown in figure 2. Irregular cycles of inundation and drying have both beneficial and destructive aspects. High flows typically lead to increased crop yields and hydroelectric production, whilst short periods of rain also help to mitigate land subsistence (Yu *et al.* 2010).

The downside of climate variability however relates to the manifestation of extreme floods and droughts (Jeuland *et al.* 2013). Floods take a significant toll on lives and livelihoods, damaging infrastructure, limiting investment, and disrupting economic activity (Dasgupta *et al.* 2011). Droughts on the other hand impact on agriculture, increase water scarcity, reduce hydropower output, and increase political tension. The impacts of drought are made worse by South Asia's lack of storage capacity (Shah *et al.* 2011). Poor water storage infrastructure has resulted in a large dependence on climatic behaviour, as a result of the regions incapacity to regulate runoff effectively (World Bank, 2013a).

One of the most vulnerable assets of the Himalayas are its glaciers. The glaciers in the Himalayas are particularly susceptible to the impacts of climate change. Matthew (2013) explains how glacial retreat is occurring very quickly in the eastern and central Himalayas. In the short term, as melt is enhanced, runoff first increases (Harrison *et al.* 2012). In the long term however, as mass balance reduces, the volume of melt water will decline, ultimately to a level that corresponds solely with precipitation (Moors *et al.* 2011). This occurs as the effect of the deglaciation discharge dividend is removed (Collins, 2008). At lower elevations, climate change is also likely to affect the timing, location, and volume of the monsoon, adding to the variability of the results shown in figure 2 (Singh *et al.* 2005).

Forecasting seasonal monsoon would be hugely beneficial in terms of water storage, energy security, management of infrastructure, and agriculture (Zhisheng *et al.* 2001). Research from the University of Reading suggests that heavy snowfall in winter and spring can lead to drought over India during the summer monsoon (UoR, 2010). The study indicates that greater snowfall reflects more sunlight, producing a cooling over the Himalayas. This in turn causes a weakening of the monsoon winds that bring rain to India (Turner *et al.* 2011). The research suggests that reduced snowfall in light of global warming will have positive impacts on South Asia's water security issues. More substantial annual monsoons however may have disastrous impacts in terms of flooding and glacial lake outburst floods (GLOFs), potentially damaging infrastructure and water quality (Singh *et al.* 2005).

Hydropower is by far the most established form of renewable energy (Agrawala *et al.* 2003). It is however affected by climate change to a far greater degree than any other renewable energy source (McDermott, 2013). As climate change becomes more recognised, different regions will see changes in rainfall, greater seasonal variability in discharge, and a greater then lesser runoff from glaciers (Moors *et al.* 2011). This ensures that a once predictable form of energy is now a source of concern for developing nations (Pomeranz, 2013).

The Hindu Kush Karakorum Himalayan glaciers are a source of water for a quarter of the global population that lives in South Asia (Laghari, 2013). Glaciers are natural stores and regulators of water supply to rivers, which in turn, provide water for domestic and industrial consumption, energy generation, and irrigation (Hamududu *et al.* 2012). The river Indus for example depends on glacial waters for half its flow (Roy, 2010). Near the rivers source however, glaciers are thinning at an alarming rate of 0.7m per year (Kaab *et al.* 2012). It is also predicted that more rain, rather than snow is to fall on mountains in the spring, causing river flows to peak before the main growing season (Wilson, 2011). Hydropower generation is also likely to be effected as its operation is directly related to a rivers runoff. Laghari (2013) for example suggests that a 1% reduction in stream flow can reduce electricity output by roughly 3%.

Traditional dam planning has always been based on the assumption that future stream flow patterns will mirror those of the past (Yan, 2012). Changes in precipitation and increases in glacial, and snow melt have however rendered this notion as obsolete (Blackshear *et al.* 2011). More frequent droughts could render hydropower projects uneconomic, while more extreme rainfall would increase the siltation of dams, reducing storage capacity, and increasing the risk of dam failures and flood releases (Harrison *et al.* 2012).

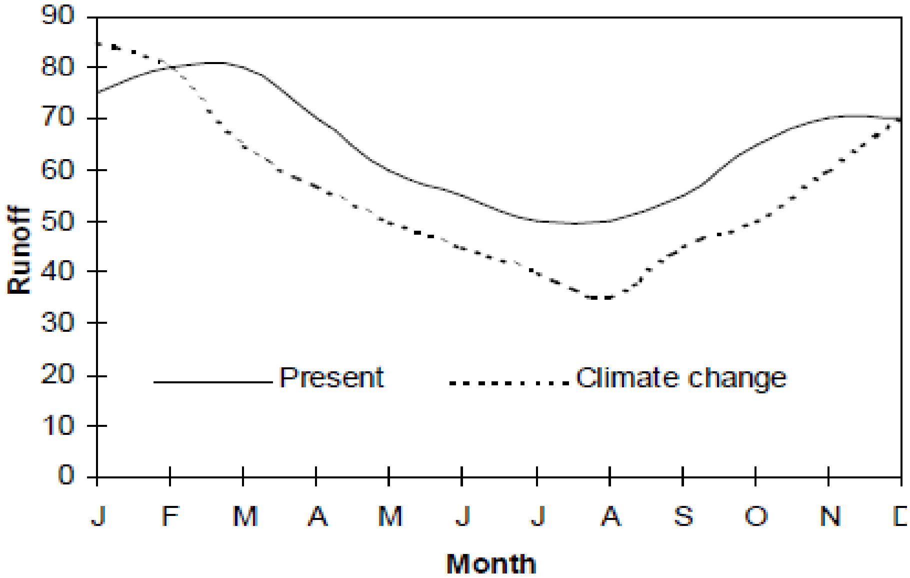


Figure 3: Predicted impact of climate change on river discharge (Harrison *et al.* 2012).

Figure 3 shows the present and future assumed data concerning the runoff of Himalayan rivers. The graph shows that winter months will see a slight increase in runoff whilst summer months will see a more reduced level of flow. Winter runoff is higher as global warming cause's precipitation to fall as rain rather than snow (Harrison *et al.* 2012). Reduced summer flow however is caused by reduced summer precipitation levels and also by a reduction in glacial mass balance, reducing glacial melt waters (Collins, 2013). Weather conditions will have a direct influence on the economic and financial viability of hydropower projects (Rebel, 2013). For example, as a result of changes in precipitation, generation rates will be higher in the spring but lower in the summer when energy is needed for cooling (Laghari, 2013).

Changes in quantity and timing of runoff, together with increased reservoir sedimentation and evaporation will have a number of impacts on the production of hydroelectric power (Hamududu *et al.* 2012). These include impacts upon system operation, financial effects, and impacts on other energy sectors (Roca, 2012). Laghari (2013) explains how hydroelectric stations are characterised by low operational costs but high capital costs. Many large hydropower developments in LDC's are built with the intention of stimulating economic growth (Whittington *et al.* 1998). This generally requires FDI. Reductions in revenue thanks to reduced runoff however, may affect a countries ability to repay their debt, severely stressing an already weak economy (Mimikou *et al.* 1997).

A lack of knowledge related to river discharge, precipitation and glacier mass balance is likely to become a problem as nations look for viable solutions to solve water and energy security issues (Turner *et al.* 2011). Laghari (2013) explains how regional goals should aim to maintain stability of flow through taking measures to limit carbon emissions, reduce glacial melting, sustain storage capacity, and maintain hydropower generation (IPCC, 1998).

2.3. Sedimentation and reduced storage capacity

Reservoir sedimentation results from the interaction of several physical processes governing the upstream sediment supply and the reservoir trap efficiency (Frenette *et al.* 1996). The sediment supply depends on the sediment source from upstream, and the sediment yield is controlled by the rivers morphology (McCully, 1996). The trap efficiency of a dam however depends on the physical characteristics of the reservoir and the particle size distribution of the incoming sediment load (Frenette *et al.* 1996).

Sedimentation reduces a reservoirs storage capacity. Water supply, flood control, hydropower, navigation, and environmental benefits are all affected by a reservoirs loss of storage (Sumi *et al.* 2005). The combination of sediment trapping and flow regulation has dramatic impacts on the ecology, transparency, sediment balance, and river morphology (Downs *et al.* 2009). A lack of downstream sediment can also cause accelerated coastal erosion (McCully, 1996). This is because clear water below a dam is said to be 'hungry'. McCully (2013) explains that clear water seeks to recapture sediment load by degrading the bed and the banks of the river downstream more rapidly, reducing its rate of aggradation.

McCully (1996) explains how in effect all rivers can be considered a body of flowing sediment as much as one of flowing water. The proportion of a rivers total sediment load captured by a dam is known as its trap-efficiency. This often approaches 100% for many projects, particularly those with large reservoirs (Munir, 2011). As sediments accumulate in the reservoir, the dam gradually loses its ability to store water. This is the case for all dams; however the rate at which this occurs varies (Lane *et al.* 1997). The quantity of sediment carried into reservoirs is at its highest during floods. In the USA for example, half of a rivers annual sediment load may be transported during only 5 to 10 days flow (McCully, 1996). During and after particularly violent weather conditions, a river may carry as much sediment as it would in several 'normal' years (Abbas *et al.* 2012). Climate change which is predicted to increase the intensity and volatility of hydro-meteorological conditions is expected to have a large impact on the rate of reservoir sedimentation, particularly within alpine locations (Munir, 2011).

2.3.1. Tarbela Dam (case study)

Tarbela dam was constructed in the 1970's on the Indus River in north central Pakistan (Roca, 2012). The project was conceived to help regulate the seasonal flows both for irrigation of the Indus and for generation of hydropower (Abbas *et al.* 2012). Providing 50% of the total irrigation releases and 30% of the total power and energy needs of Pakistan, Tarbela is a hugely important national resource (Tribune, 2010).

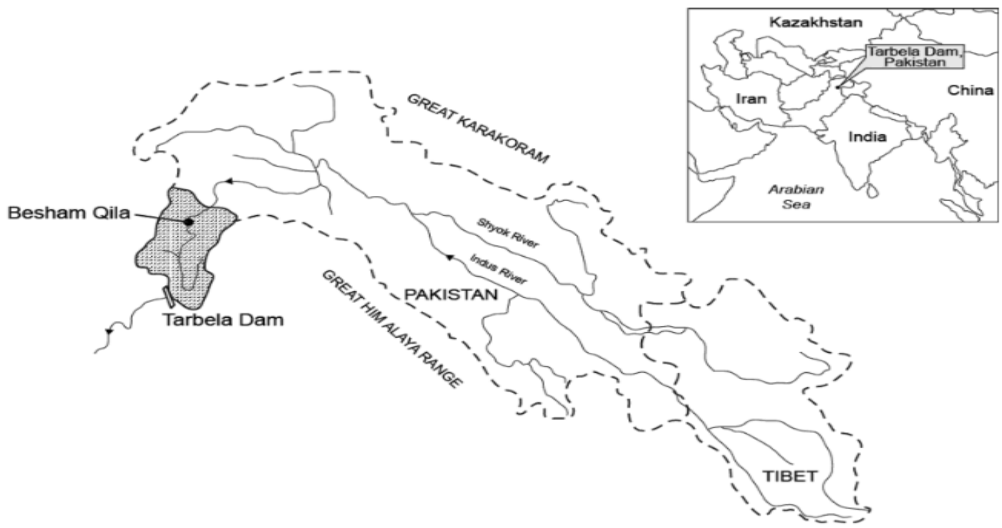


Figure 4: Map of Tarbela dam and its catchment area (Ali *et al.* 2007).

The Indus basin upstream of Tarbela has an area of 169,650km^2 (Tate *et al.* 2000). Over 90% of this lies between the Great Karakorum and the Himalayan ranges (Roca, 2012). Melt waters from this region contribute toward a significant proportion of annual flow reaching Tarbela (Sanchez *et al.* 2009). The remainder of the basin lying upstream of the dam is subject to monsoon rainfall during July, August, and September (Ali *et al.* 2007). Runoff from the monsoon causes sharp floods of short duration which are superimposed on the slower responding snowmelt runoff, shown in figure 5 (Roca, 2012). It is important to mention that 94% of the rivers total catchment area lies outside of the monsoon belt, which shows how heavily the river relies on glacial and snow melt for its discharge (Abbas *et al.* 2012).

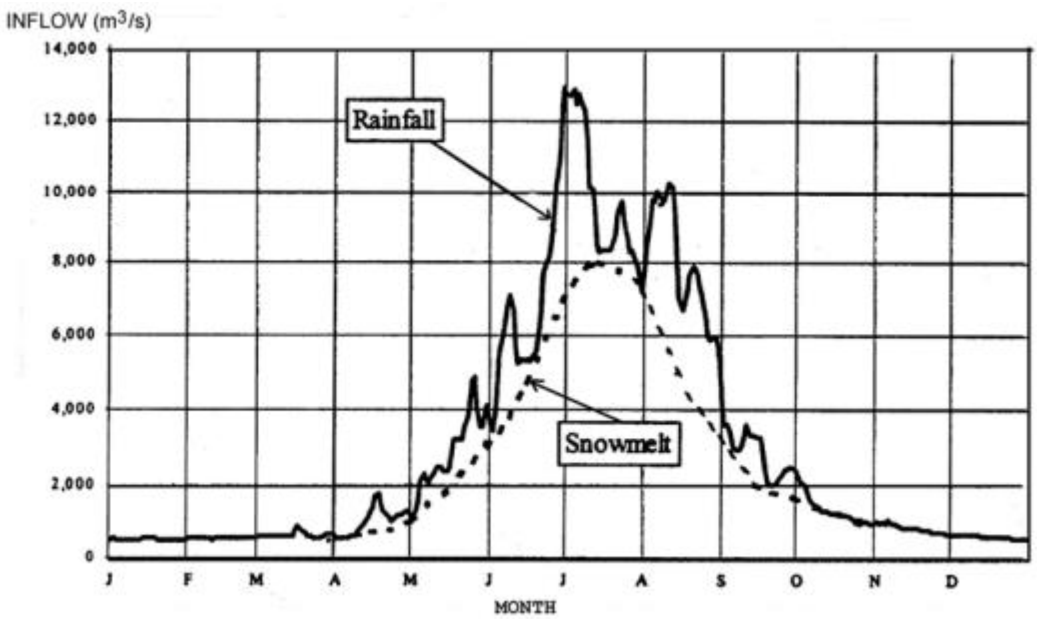


Figure 5: Average monthly inflow in Tarbela Reservoir as a result of both rainfall and snowmelt (Roca, 2012).

The upper Indus River basin has one of the highest rates of sediment transport reported in modern literature (Meybeck, 1976). The sediment rich water creates many water resource management problems. These include problems such as reduced capacity, turbine damage, reduction in water quality, and transport of chemical pollutants (Ali *et al.* 2007). An understanding of the patterns of suspended yield in the Indus is therefore essential for effective future water resource development (Knighton, 1998).

The Karakorum and Himalaya regions are examples of young mountains, subject to exceptionally rapid degradation (Searle, 1991). Tectonic instability and high relief, combined with runoff from glaciers can also result in extremely high sediment yields

(Collins *et al.* 1995). In specific areas of the basin, another important factor is human activity involving deforestation, agriculture, and the development of infrastructure (Ali *et al.* 2007).

2.4. Trans-boundary Issues (A Regional Paradox)

The most important links between the countries of South Asia are its rivers (Dharmadhikary, 2008). Almost every major river is a trans-boundary one. The Indus River for example, originates in Tibet, travels through India and then into Pakistan, before eventually running into the sea (Hangzo, 2012). Political boundaries however cut sharply through the region. Areas that hold common geographical, topographical, and eco climatic features, may also share starkly different political and economic contexts (Dharmadhikary, 2008). Nepal and Bhutan for example continue to be primary production economies with low industrialisation and high agricultural dependency (Wirsing, 2010). Pakistan and India however are much more industrialised. As a result, development policies, priorities and constraints also differ in each of the four countries (Prasai *et al.* 2013).

China is becoming increasingly recognised as a very large player with relation to trans-boundary conflicts in South Asia (Hangzo, 2012). China is seen as a nation that is taking advantage of its commanding position as the source of trans-boundary rivers, by using it's rivers as a 'weapon' (Chellaney, 2011). According to this argument, China sees its rivers as a means of asserting power over its lower riparian neighbours (Wirsing, 2010). Chellaney (2012) argues that the weaponisation of shared rivers has led to the nations of South Asia to engage in a race to build a great number of dams. This race for control is primarily the result of all nations desire to ensure sustained economic growth (Hangzo, 2012).

It is strongly believed that Chinas relationship with India is likely to determine the future of the region's water security, as both countries are the regions hydro-hegemons (Grey *et al.* 2011). China as the upstream power particularly has the ability to control the quality and flow of the water that reaches riparian regions (Turner *et al.* 2013).

Turner (2013) argues that China exercises its hydro-hegemony by refusing to sign water sharing agreements or water management treaties with lower riparian countries. China also does this through pursuing unilateral actions such as building dams without consulting countries downstream (Hangzo, 2012). China not only controls the headwaters of these rivers but it is also the most powerful state in the region economically, and militarily (Turner *et al.* 2013). As a result, China has little incentive to enter into formal cooperative water agreements with its neighbours (Wirsing, 2013). To meet Chinas hydropower goals the central government has proposed the construction of 60 medium and large dams by 2016. These dams are primarily focused on rivers flowing out of the Himalayas into South and South East Asia, threatening the water security of downstream nations.

A good gauge of the trans-boundary significance of rivers originating from the HKH region is the water dependency ratio (Turner *et al.* 2013). Water dependency ratio is an index that measures the volume of water resources originating outside a country and highlights the potential vulnerability of shared waters to competing interests (Cook *et al.* 2013).

Table 1: Water dependency ratios of countries throughout the HKH region (Munir, 2011).

Central and South Asia	Water Dependency Ratio (%)	East and Southeast Asia	Water Dependency Ratio (%)
Afghanistan	15	Cambodia	75
Bangladesh	91	China	1
India	34	Laos PDR	43
Kazakhstan	31	Myanmar	16
Kyrgyzstan	0	Thailand	49
Nepal	6	Vietnam	59
Pakistan	77		
Uzbekistan	77		

As shown in table 1, an examination of these ratios among multiple states in the HKH region reveals a sharp imbalance. China has a dependency ratio of only 1% for example making it one of the most hydrologically self-reliant countries in the world (Hangzo, 2012). At the other end of the scale however, Bangladesh and Pakistan, which at 91% and 77% respectively, are two states that are most dependent on water from outside its borders (Cook *et al.* 2013).

2.5. Water sharing agreements

Most of the rivers of the HKH region lack any treaty among riparian countries and each has different and conflicting plans for development in the basin (Cook *et al.* 2013). China believes that harnessing its rivers is essential to addressing its energy and water needs (Turner *et al.* 2013). As a result, China builds dams on shared rivers despite objections from lower riparian neighbours, as it is not constrained by any legally binding water sharing agreements (Jayaram, 2013). In 2006 however, China set up a joint expert level mechanism with India. Within this they discussed cooperation on the sharing of hydrological data, emergency management, and other trans-boundary river issues (Hangzo, 2012). This cooperation led to the establishment of the Himalayan River Commission (HRC) which focuses on the management of shared rivers (Dsouza, 2013). Representatives from Bangladesh, China, India, and Nepal now attend annual meetings as a result of the HRC, showing that there is interest in a cooperative arrangement (SFG, 2011).

The Mekong River Basin Commission (MRC) is a rare example of a successful multilateral cooperation (see Figure 6). The river originates in China and flows through Myanmar, Laos, Thailand, Cambodia, and Vietnam. The MRC formed in 1995 aims to encourage balanced and coordinated developments and investments in irrigations and drought management, hydropower, flood management, water shed management, environment and tourism (Cook *et al.* 2013). China in particular has agreed to share information on its rivers flows and dam operations.

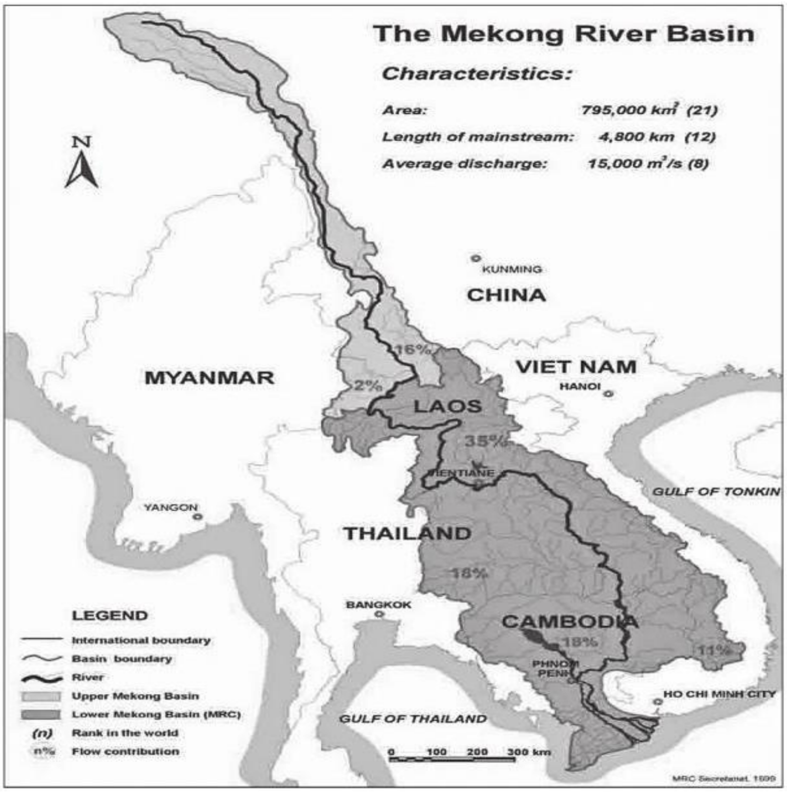


Figure 6: Map of the Mekong River basin (Rebel, 2013).

Distribution of rivers is largely determined by hydro politics rather than water availability (Roy, 2010). The Indus River Treaty, signed in 1960, divides the Indus River Basin along the India/Pakistan border. The treaty defines the principles for sharing water of the Indus River between India and Pakistan (PILDAT, 2012). Issues have been raised however regarding how the waters were divided to begin with. Pakistan for example has voiced concerns over India's potential to disrupt flows into Pakistan by damming the upper reaches of the Indus (Wirsing, 2013).

Nepal and Bhutan are uniquely positioned with respect to their upstream location and abundant hydropower potential (Cook *et al.* 2013). The two countries share numerous agreements with India in relation to flood control and hydropower (Wirsing, 2013). In 1996 Nepal and India signed the Mahakali Treaty for integrated, multipurpose development of the river (Hearns, 2007). There is growing concern however that India's growing energy demand for hydropower is unequal and monopolistic (Bhushal, 2014). Hearns (2007) acknowledges a lack of mechanisms used to enhance cooperation between Nepal and India as a significant reason for the failure of the treaties implementation. It is also understood that climate change is partially to blame for the collapse of the treaty (Bhushal, 2014). The realisation of a shorter rainy season and reduced runoff in future years made the treaties implementation even more problematic (Tobassum *et al.* 2004).

Chinas reluctance to move in the direction of water transparency is a formidable road block to regional cooperation on water security (Wirsing, 2013). In 2013 China rejected a proposal by India to create a new water commission between the two nations (Turner *et al.* 2013). There are fairly strong signs however that South Asian governments are increasingly inclined to cooperate on the issue (Shah *et al.* 2013). In April 2013, Nepal, India, and Bangladesh forged an important agreement to jointly exploit hydropower and manage water resources for mutual advantage (Mehdudia, 2013). It is difficult to see how this venture can be hugely successful however without cooperation from China.

Research reveals that a change in environmental conditions that outpaces the capacity of existing institutions to cope with such change is a cause of tension (Uprety, 2012). Conflicts related to sharing remain unresolved due to a lack of norms to manage water flows and flexible mechanisms to deal with changes (Salmon *et al.* 2011). Riparian states often feel vulnerable to rising flow variability, and favour the use of variability management mechanisms (Drieschova *et al.* 2008). Uprety (2012) explains how it is now becoming realised that trans-boundary agreements being rigid instruments entailing high opportunity costs for modification are less ideal compared to those that are more flexible.

2.6. Economic growth models

Geographers often seek to categorise places using a scale of development, frequently dividing nations between 'developed' and 'developing' for example (Jacobs, 2013). All countries aim to achieve economic growth. Economic growth is the growth in the economic wealth of countries for the well-being of their inhabitants, through the concerted actions of policy makers and communities (SVBIC, 2011). There have been a number of economic growth models developed over recent years that look to try and simplify the complexities of economic development.

Economic growth depends critically on access to reliable energy (Greenstone, 2014). In South Asia particularly however, connectivity remains low, supply in connected areas is unreliable. and carbon emissions are on the rise (McMillan, 2008). Physics shows that energy is crucial for economic growth, but the mainstream theory of economic growth often pays no attention to role of energy (Stern, 2010).

Howitt (2009) also explains how the principle economic models used to explain the growth process, do not include energy as a factor that could constrain or enable economic growth. Energy is essential to all economic production. As a result, criticism of growth models that ignore energy is legitimate. Models such as the Harrod-Domar growth model, Lewis's Structural change model, and Rostows five stages of economic development are all well recognised pieces of work; however each of them does not include the importance of energy. Theories that try and explain growth entirely as a function of energy supply are also incomplete however.

Research by Stern (2010) suggests that long term energy availability could constrain economic growth. This conclusion emphasises how critical reducing energy security has become. Two models of development can however be modified to relate to whether hydropower could be a viable influence over issues relating to energy security. Boserups and Malthus's models of resource consumption can be revised to relate to energy.

Both have opposing theories on what happens when resources fall short of a population's demands. Both theories primarily relate to the subject of food consumption. Malthus expresses a pessimistic view over the dangers of population growth and claimed that food supply was the main limit to population growth (thinkgeog, 2008). Malthus explained that population growth would increase demand on food supply, eventually reducing food production as a result of increased pressures over production (Reynolds, 2013). His theory is based upon the law of diminishing returns (Malthus, 1798).

Boserups theory however can be summed up by the sentence 'necessity is the mother of invention' (thinkgeog, 2008). Boserups theory suggests that demand for food acts as an incentive to adapt and innovate (Adnane, 2010). As a result population growth becomes sustainable thanks to spark innovators improving food production methods.

This theory of resource consumption can relate directly to issues within Asia if food production is replaced with energy production. There is ever increasing concerns over meeting growing demands for energy. Malthus's theory would suggest that shortfalls in energy will prevent further population growth. He would also argue that further attempts to increase production would inevitably reduce overall efficiency, reducing supply. This potentially relates to the belief that the greater realisation of climate change will reduce the future efficiency of hydropower.

Boserups theory however would suggest that as demand for energy increases, technical innovations will cover shortfalls in energy supply through improved production. The development of hydropower could be viewed as this production increasing innovation. Hydropower in Asia can be appreciated as a very current and innovative way to more economically and sustainably meet growing demand. Whether it is capable of continuing to meet such demand in light of increasing political and environmental concern is however unknown. Boserup would argue though that sustained shortfalls would have to trigger further innovation to increase production, therefore potentially leading to a major growth in hydropower investment.

3. Methods

3.1. Methodological considerations

In light of climate change, population growth, and in some states economic poverty, hydropower fails to be viewed as a viable investment. The potential opportunity for improved energy, water and food security however catches the interest of powerful political figures. Controlling the runoff from one of the most affluent fresh water regions on the planet is a fantastic opportunity for Asia to more effectively accommodate growing populations. Constructing dams and reservoirs along the trans-boundary rivers that feed South Asia could allow for economic, population, and energy growth on a greater scale.

The impacts of climate change on hydropower are also analysed in detail, as hydro meteorological change affects the morphology of the river and the properties of the runoff. This has a direct influence on the efficiency and economic significance of a potential hydropower investment. Hydropower is the most prevalent source of white energy on the planet. The objective of the research is to analyse how effective and successful a large scale investment could be in Asia considering the potential impacts of climate change and the demands of population growth. This is of particular importance in view of large scale developments already forecast in China and India.

Asia is a diverse hydropower market characterised by growing economies and plentiful resources (Trembath, 2015). With GDP growth rates of between 4 and 8% across Asia the regions huge demands are being placed on countries to rapidly expand their energy sectors. The World Bank (2013) argues that despite contentious environmental and social impacts within Asia, hydropower has enormous potential to open avenues for growth within local economies. More recently South Asia has also been the main area of focus for leading figures in water and energy to gather. In May this year the 2015 Hydropower congress was held in Beijing for example (Trembath, 2015). Asia can also be seen as an appropriate case study for hydropower due to Chinas world leading position in relation to hydropower generation figures. The Three Gorges Dam power station exceeded the world record for annual generation in 2014 (Trembath, 2015). Along with existing hydropower stations, China is also showing exponential intent in terms of further investment. This understanding is supported by the recent completion of the Xiluodu project on the Jinsha River which is currently recognised as the world's third largest power station (Greenstone, 2014).

Asia is viewed as an appropriate case study due to its mountainous topography, its many glacier fed rivers, and its existing and proposed developments (Laghari, 2013). Particular focus is however aimed toward changes in the flow of the River Sutlej which is a tributary of the River Indus. The River Sutlej acts as an ideal case study to analyse due to its huge untapped hydroelectric potential and its vulnerability to environmental and social externalities (Miller *et al.* 2012). In economically emerging regions such as Pakistan and India that possess economies that are closely tied to their natural resource base, vulnerability to the impacts of climate change are enhanced (Sharif *et al.* 2011). This accompanied by the River Sutlej's alpine location makes hydropower's feasibility within this river system particularly susceptible.

Through support from the World Bank the Indus Basin Project was initiated in 1978 in Pakistan in an attempt to control the unregulated flows of the Indus River (Water-Technology, 2015). Seasonal variations in river flow and a lack of storage reservoirs to conserve surplus flows causes issues in relation to both water and food security for Pakistan. Within this project existed the construction of Tarbela dam which was built to primarily regulate flows for irrigation use (World Bank, 2013). It was also developed to achieve substantial hydroelectric generation. Tarbela Dam can be recognised as an ideal case study within this thesis due to its vulnerability as a feasible economic investment. Mitigation strategies are also in place in attempts to prolong the dam's life span amid fears over sedimentation (Schneider, 2008). An example of this refers to the construction of Diamer-Basha Dam upstream of Tarbela (Water-technology, 2015).

Finally, to help understand how the development of hydropower has changed already through time, dams in India are analysed in relation to completion dates and capacity. The locations of these dams throughout India are also examined, as is the relationship between the time of construction and the size of the dam. Only the five states of India that border the Himalayas are used as case studies however.

3.2. Approach

Secondary research represents the main instrument of the background. It also represents the theoretical background to which conclusions made from the research can be analysed against. Secondary sources of data are also fully utilised in the practical part of this research.

Runoff data has been collected from the river Sutlej in Pakistan to help assess the potential future of hydropower as a significant energy source. Analysing the change in runoff and timing of peak flows is important in understanding how climate change could impact on the efficiency of hydropower. Understanding runoff patterns could play an important role in the future successful design and mitigation of hydropower, as current projects are still developed based on the knowledge that climate conditions have remained stationary.

Data such as this was acquired through research into the World Bank, which is particularly helpful in terms of accessing development indicators for countries throughout the world. Asia policy journals also contributed relevant data, as did the KNMI climate explorer which is a web application that analyses climate data statistically. Data such as precipitation levels and air temperature from a variety of different gauging stations across Asia can be sourced from this web page. It is also possible to gain data relating to river discharge from this source; however this data is often irregular and inconsistent. The Indian Water Portal is another statistical web page that was used. Data from this web page covered indices such as precipitation, air temperature, cloud cover, and vapour pressure for example. This information is obviously only available for Indian states however.

Primary data was not utilised throughout this research. This is partly due to the hostility of the locations that would have needed to be visited, and also due to the magnitude of data that was already accessible online, in journals and articles, and from the authors tutor. Primary data would have added greater depth to the research, however the time period needed to generate the desired data is too great for it to be a realistic option.

3.3. Study Area

The study area for this thesis is the Himalayan region and the downstream basins of the rivers that are sourced there. The Himalayas is an 800km long mountain region that stretches between central Afghanistan and northern Pakistan (Daly, 2013). The water resources of the region, sustain approximately 150million people. The region is also shared by eight countries (Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan) and interleaves with Asia's eight major river basins (Indus, Ganges, Brahmaputra, Irrawaddy, Salween, Mekong, Yangtse, and Yellow River) as shown in figure 8. The Himalayan region is the highest mountainous region in the world and is characterised by great geological, biological and cultural diversity, as well as extensive marginalisation and poverty amongst its people (Sticklor, 2012).

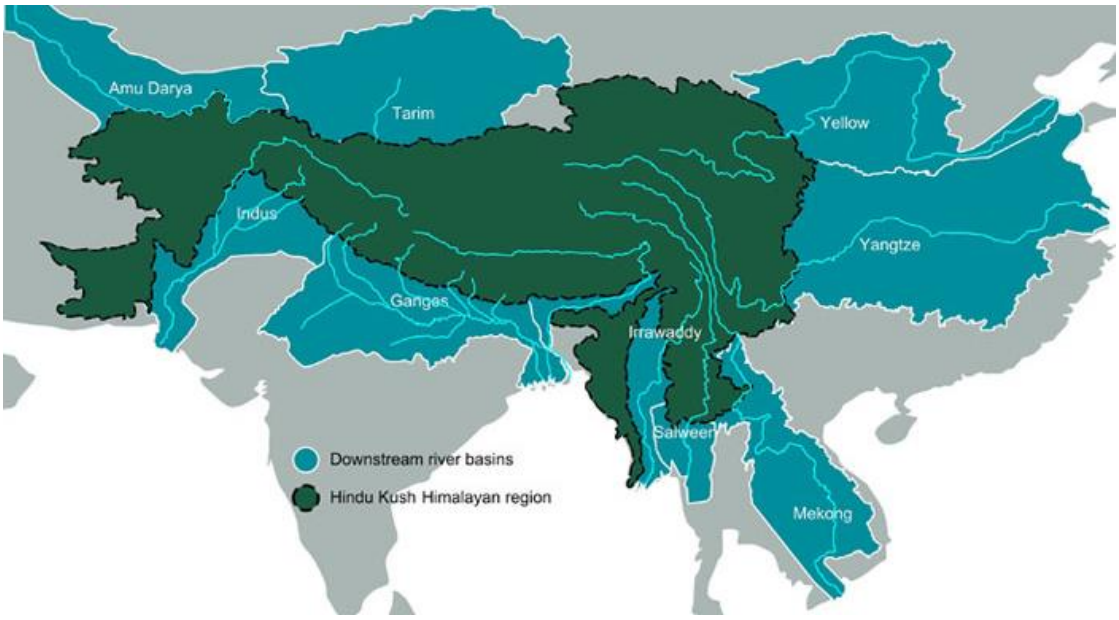


Figure 7: Map of the Hindu Kush Himalayan region and the river basins that surround it (Hangzo, 2012).

The Himalayan region is home to 30% of the world's glaciers and is often referred to as the 'third pole'. It is also one of the most ecologically sensitive and fragile regions in the world. The effects of climate change are likely to be more evident here and perhaps have the greatest impact, since this ecosystem supports the livelihoods of more people than any other coherent ecosystem in the world (Newcomb, 2013).

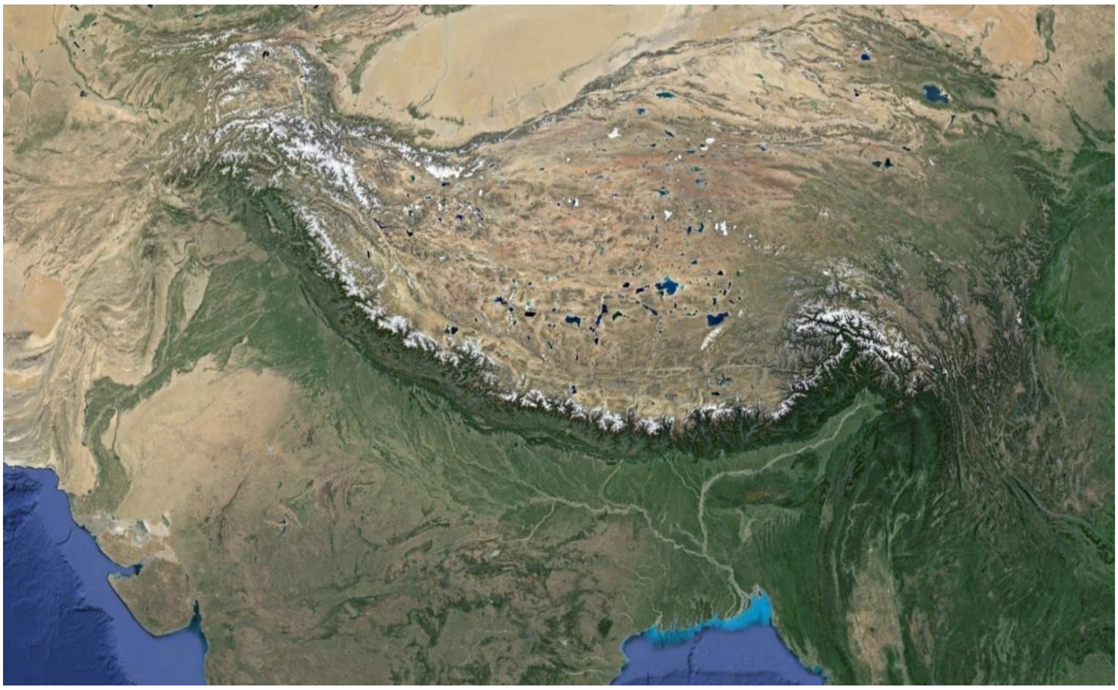


Figure 8: Google earth image of the Hindu Kush Himalayas (Google Earth, 2014)

Table 2 shows the glaciers and the glaciated area in the major basins on the Hindu Kush Himalayan region. This information is significant considering in some circumstances glacial melt makes up 80% of a rivers annual runoff.

Table 2: Glaciers and glaciated area in the basins of the Hindu Kush Himalayan region (ICIMOD, 2011).

Basin	Basin area within HKH (km²)	Number of glaciers	Glaciated area (km²)	Estimated ice reserves (km³)	Average glacier area (km²)
Amu Darya	166,686	3,277	2,566	162.61	0.78
Indus	555,450	18,495	21,193	2,696.05	1.15
Ganges	244,806	7,963	9,012	793.53	1.13
Brahmaputra	432,480	11,497	14,020	1,302.63	1.22
Irrawaddy	202,745	133	35	1.29	0.27
Salween	211,122	2,113	1,352	87.69	0.64
Mekong	138,876	482	235	10.68	0.49
Yangtze	565,102	1,661	1,660	121.40	1.00
Yellow	250,540	189	137	9.24	0.73
Tarim Interior	26,729	1,091	2,310	378.64	2.12
Qinghai-Tibetan Interior	909,824	7,351	7,535	563.10	1.02
Total	**3,705,721***	**54,252**	**60,054**	**6,126.85**	**1.11**

*An additional 486,725 km² non-glaciated area lies outside the basins.

Increases in glacial melting are projected to limit the natural water storage provided by expanses of snow and ice and are expected to heighten the risk of glacial lake outburst floods (Climate Himalaya, 2013). Mass losses from glaciers in the Himalayas and accelerating reductions in snow cover are expected to ultimately reduce water supplies and hydropower potential. Changes in the seasonality of flows supplied by melt water are also predicted. Droughts will affect greater areas, resulting in greater reliance on irrigation, whilst there will also be an increased risk of flooding thanks to an increase in climate variability (Vidal, 2013).

Before research was carried out, a detailed evaluation of the Himalayan region was undertaken, including an analysis of its rivers, reservoirs, hydropower developments and the regions vulnerability to climate change. This was done to ensure that the most relevant and significant case studies were analysed.

A variety of case studies were utilised throughout this thesis in an attempt to develop a detailed understanding of the following relationships:

- The impact of climate change on the volume and timing of river discharge;
- The changing efficiency and productivity of current hydropower developments;
- The change in the frequency of dam development and the relationship between date of completion and storage capacity;

- Patterns and rates of sedimentation in reservoirs and its impacts on storage capacity and hydropower;
- The feasibility of hydropower in relation to economic opportunity and the relationship between local GDP, population growth, and hydroelectric generation.

3.4. River Discharge

Two rivers were preferred for analysis after evaluation of the study site. The river Indus and river Sutlej both possess huge hydropower potential, and supply a huge area of South Asia with freshwater. They are also extremely vulnerable to the potential impacts of climate change. Both are also crucial in relation to water storage, particularly in light of population growth and more irregular river runoff. The majority of the research is however aimed at the River Sutlej thanks to an abundance of accessible data. The River Sutlej is the easternmost tributary of the River Indus (figure 10). It enters India through Himachel Pradesh, before heading South West to meet the river Beas in Punjab state.

The river Sutlej is the longest of the five rivers that flow through Punjab in Northern India and Pakistan. The river is 1,450km long and there are various hydroelectric power and irrigation projects along the river including the Kol Dam, Bhakra Dam, Baspa hydroelectric power project, and Nathpa Jhakri project (SANDRP, 2013). The overall hydroelectric power capacity in Himachel Pradesh is evaluated to be 20,000MW of which around 50% is from the Sutlej valley (Shukla, 2014).

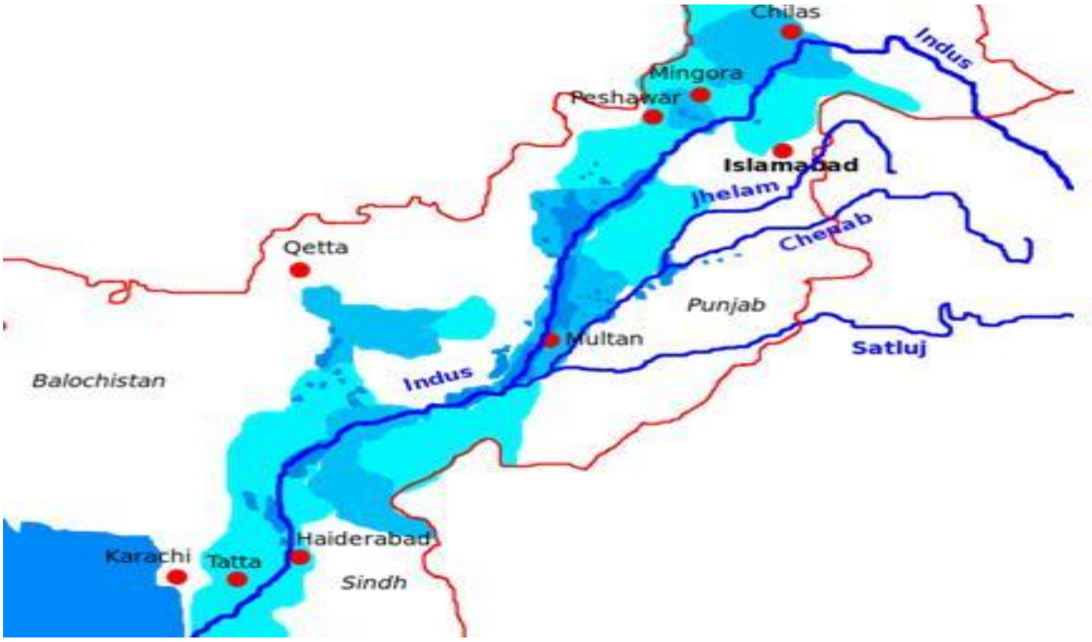


Figure 9: Map of the River Indus basin, showing the location of the River Sutlej tributary (Abbas *et al.* 2012)

Discharge data has been sourced from two different gauging stations along the River Sutlej. These include Khab and Rampur stations (shown in figure 11). Comparing discharge data at different locations helps to develop a more detailed understanding of where the greatest changes are being realised and how change differs with distance from a rivers source. Air temperature and precipitation levels over the Sutlej river catchment are also analysed so that any correlations between discharge and hydro-meteorological change can be discussed. It is particularly important that variations in discharge are analysed along the river Sutlej as it feeds Bhakra dam, which is essential in India thanks to its storage capacity and hydroelectric generation potential.

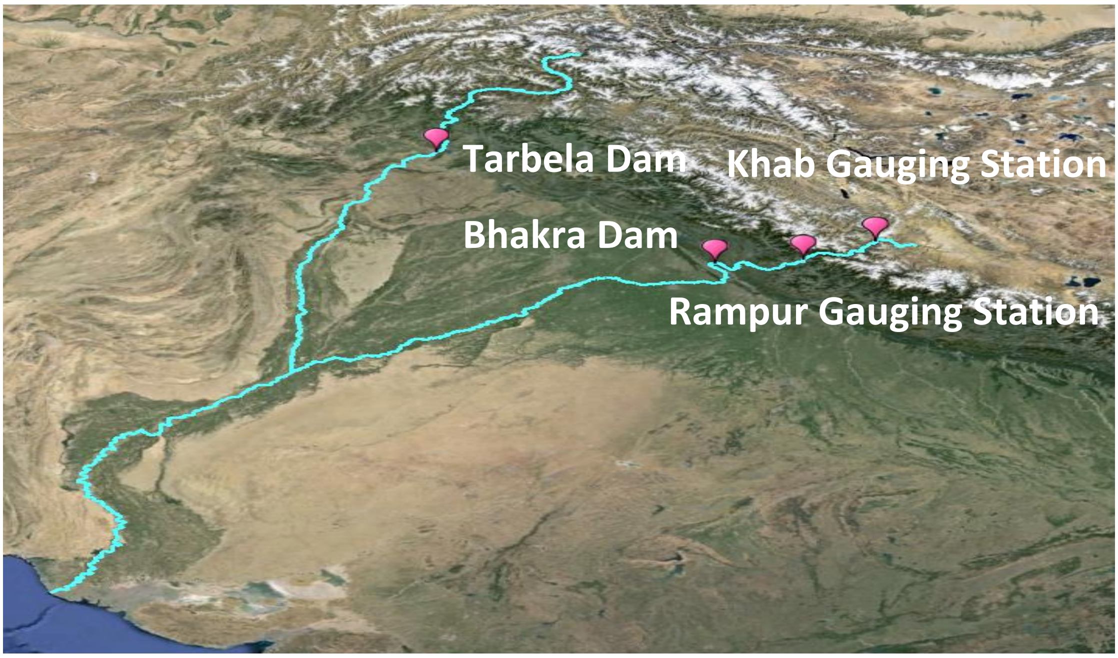


Figure 10: Google earth image showing the locations of the stations where data has been sourced from (Google Earth, 2014)

3.5. Changing philosophy toward Indian dam construction

India was chosen for this area of research because of the large level of access to data concerning dam size, completion dates, dam locations, and storage capacity. Similar data for dams within Pakistan for example was not available. To study dams that are more relevant to the research, developments from only within the five Himalaya bordering states of India have been utilised. These states include Arunachel Pradesh, Himachel Pradesh, Jammu &Kashmir, Sikkim, and Uttarakhand.

Figure 11: Map showing the location of the five Indian states that border the Himalayas (Harmon, 2011).

Within this section of research, the number of dams that exist within the five bordering states is displayed. The years in which these dams were built are also presented and the storage capacities of the dams that exist within these states are shown. Finally, the relationship between the size of dams and the year in which they were built is displayed so that any change in dam building philosophy can be understood. Understanding how dam building has changed already through time will make it easier to make predictions on how dams are likely to look and be developed in the future.

3.6. Changing efficiency of current hydropower

To understand how hydropower is already changing in South Asia as a result of externalities it is important to first analyse how existing hydropower has changed. For this area of research three rivers were studied. These include the river Sutlej, river Indus, and river Chenab. All rivers have been heavily developed in terms of generation capacity and water storage. The locations of all three rivers can be understood through figure 10. Both the river Indus and Sutlej have already been discussed however the river Chenab is only referred to in this section of research. The river Chenab is also a tributary of the river Indus. It forms in Himachel Pradesh, flows through Jammu & Kashmir and then into Punjab. The waters of Chenab are completely allocated to Pakistan under the terms of the Indus water treaty.

The following two figures show maps of all the proposed hydroelectric projects within both the river Sutlej and river Chenab. These figures show where along these river catchments that projects exist and where they are being proposed to be built. The figures help to demonstrate the scale in which development has already occurred along these catchments and the remaining potential for future investment. These figures have also allowed the author to demonstrate to the reader how important each of these river catchments is in terms of energy production and future energy security prospects.

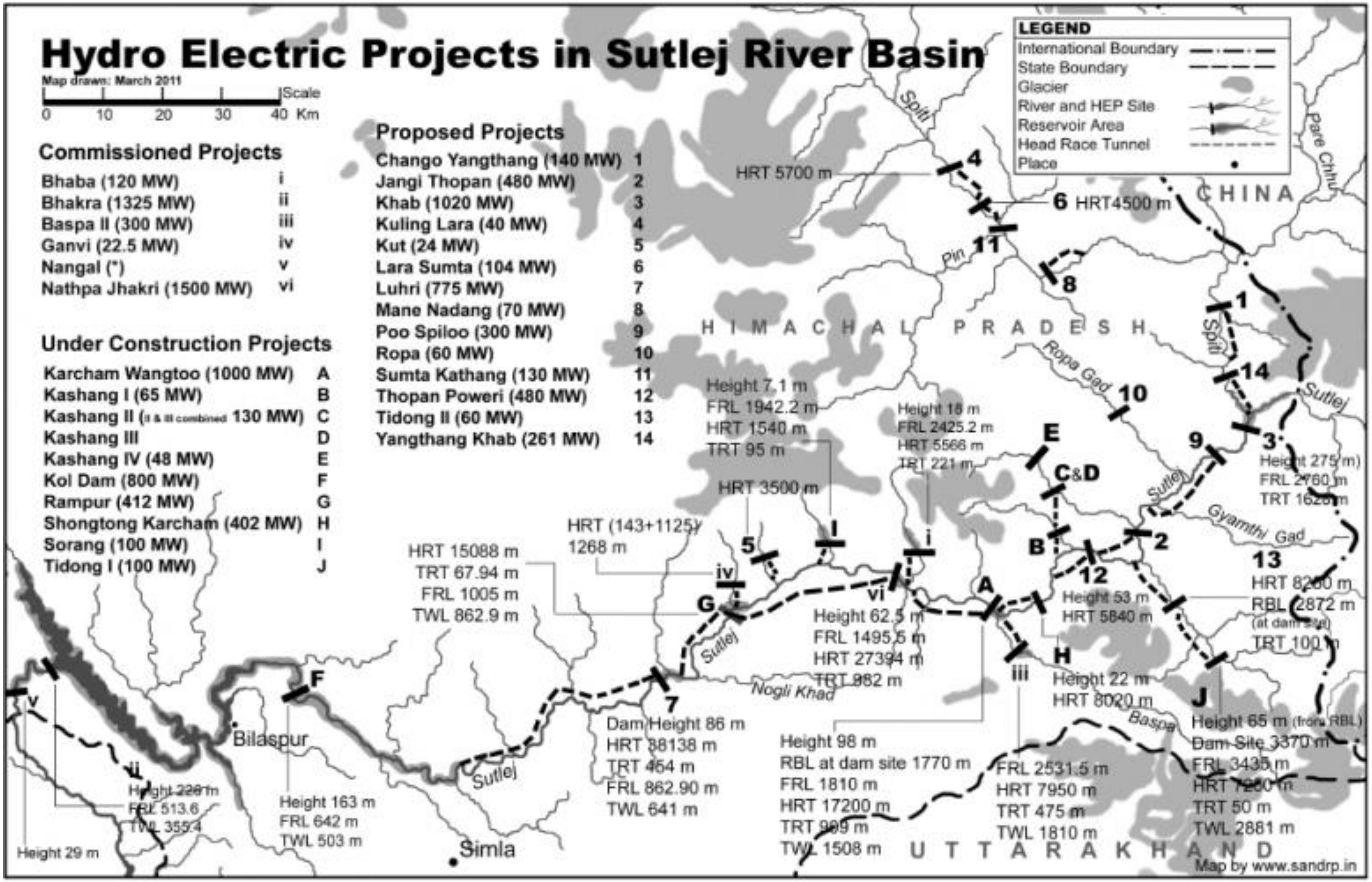


Figure 12: Map showing the commissioned, under construction, and proposed hydroelectric project along the River Sutlej basin (Mehta, 2011)

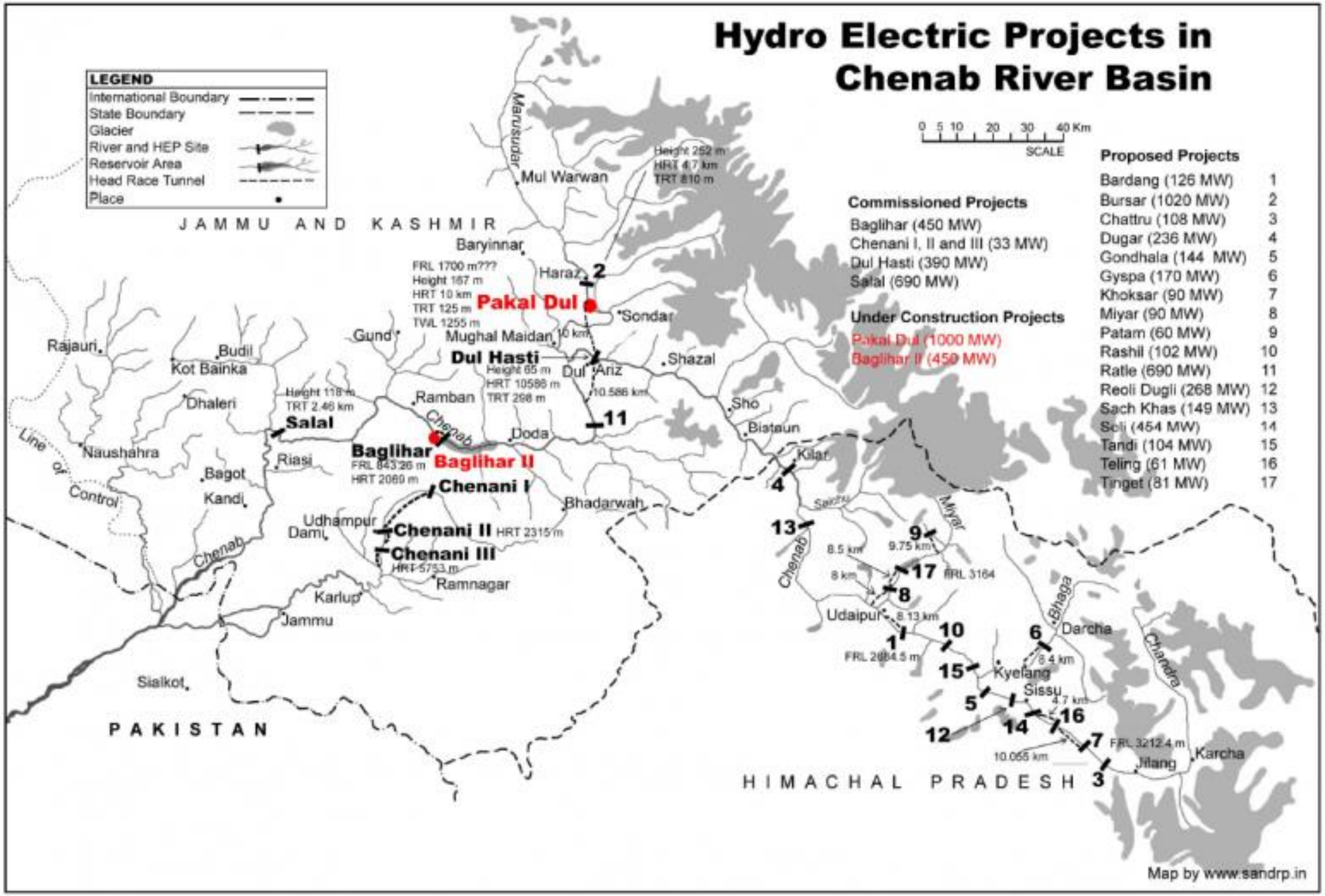


Figure 13: Map showing the commissioned, under construction, and proposed hydroelectric projects along the Chenab river basin (Mehta, 2011)

3.7. Sedimentation and storage capacity

Under this subheading of research, Tarbela Dam has been studied to generate an understanding of the impacts sedimentation is having on some of the largest and most significant dams in South Asia. Tarbela Dam is the largest earth filled dam in the world and the second largest by structural volume. Completed in 1974, the dam was designed to store water from the Indus for irrigation, flood control, and hydropower generation (Roca, 2012). Tarbela is a strategic natural resource providing 50% of the total irrigation releases and 30% of the total power and energy needs for Pakistan. As shown in figure 15, Tarbela Dam is located near the small town of Tarbela in Haripur District, Khyber Pakhtunkhwa, about 50km northwest of Islamabad (Ahmad, 2014)

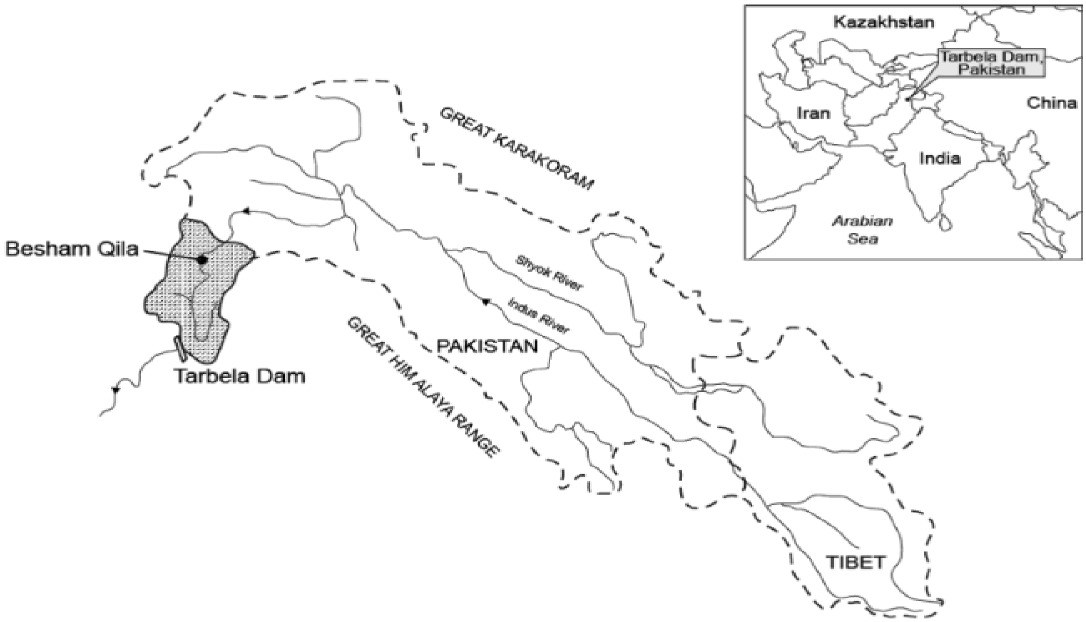


Figure 14: Map of the River Indus drainage basin and the location of Tarbela Dam (Roca, 2012).

Tarbela reservoir has a catchment area of 168,000km^2 and an installed generation capacity of 3478MW (Harris, 2015). Tarbela has an extremely high trap efficiency and the annual sediment load is approximately 430 million tonnes, making sedimentation rates extremely fast (WAPDA, 2014). Research into the rate and level of sedimentation has been carried out so that reasons for the reservoirs loss in capacity can be analysed. Profiles of the Tarbela reservoir are studied with reference to rates of sedimentation and future estimates are also calculated using existing data and future predictions of discharge levels and sedimentation rates. Cross sections of the reservoir are also displayed in the results chapter of this thesis at 5 different sites to generate a better understanding of how sedimentation is occurring differently at different locations within the same reservoir (see figure 17). A schematic view of Tarbela reservoir is seen in figure 16.

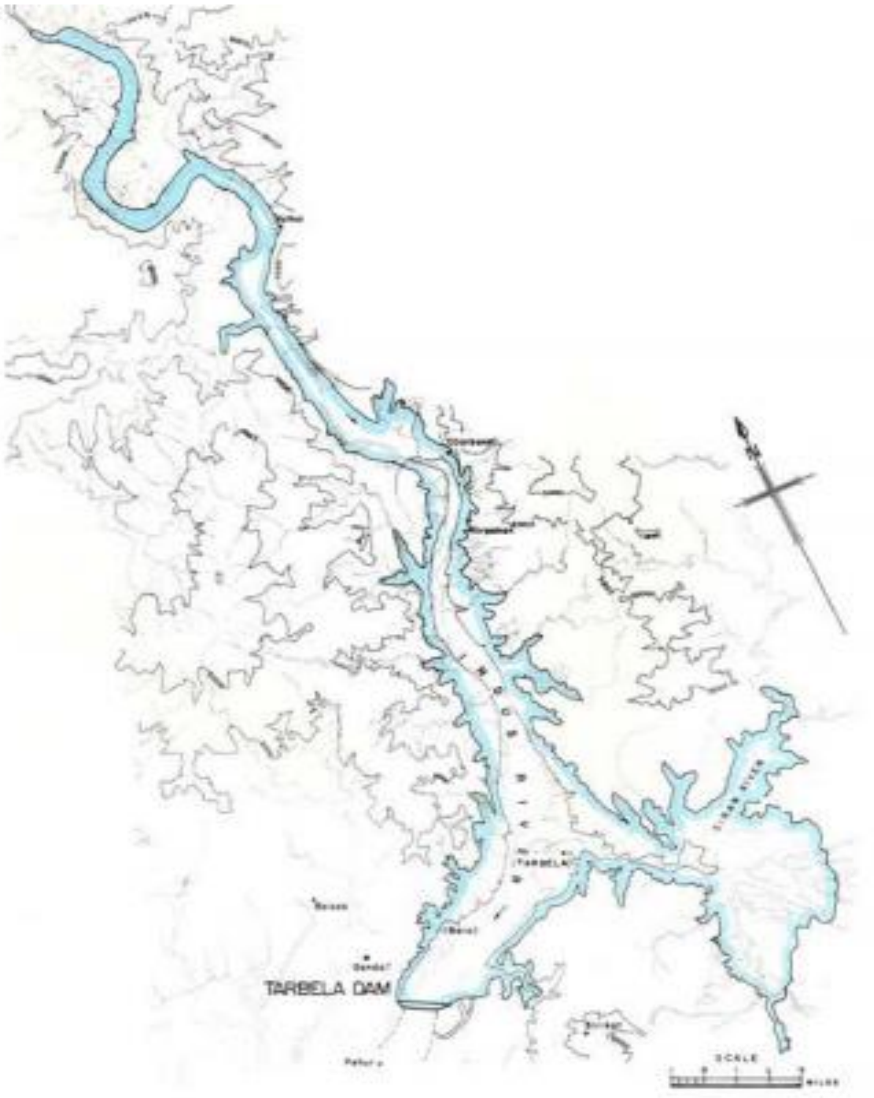


Figure 15: Schematic view of Tarbela reservoir (Munir, 2011)

Figure 16: Google earth image showing the 5 locations along Tarbela reservoir where sedimentation data was sourced from (Google Earth, 2014)

3.8. Economic growth prospects

Research under this subheading focuses on data from the World Bank. This data includes population growth, GDP growth, electricity generation, and percentage hydropower for example. The relationships that exist between these indices will differ between nations i.e. between Nepal and China, however understanding how one factor influences the other would be beneficial in terms of planning future hydropower investments. China, India, Pakistan, and Nepal have been researched. This should develop an interesting spectrum of research considering the difference in each country's economic and political positions. The results from this research also give an insight into how reliant each nation is on hydropower generation and looks into the countries capacity to survive without it if climate change renders the energy source as uneconomic.

The results found from this research are then cross examined with existing models of development, to see whether hydropower can initiate regular patterns of economic growth. Rostows model of development, and Malthus and Boserups population theories are referenced to see if the results of an investment in hydropower are to be consistent with what their theories suggest.

3.9. Limitations

Like in any research of this type, there were difficulties with accessing certain data sets. The overall quality of the data presented in the following chapter however is more than satisfactory.

Before the research commenced it was clear that the collection of primary data was not plausible because of a combination of the location of the study area and the lack of appropriate apparatus and equipment needed to carry out the necessary research. As a result this thesis relies completely on secondary research. Obtaining thorough and reliable secondary data however also posed issues, as much of the data available online was incomprehensive, irregular and unbalanced. This was particularly the case for the generation values obtained for Tarbela Dam. Much of this data was irregular and covered an insignificant time period. Attaining this data took longer than anticipated and it was also a challenge to make significant comparisons using this data, as overlapping years of data from all sources were difficult to find. As a result, this data has not been included within the results section.

4. Results

This chapter displays the results from the research covered throughout the data collection process of the thesis. The more relevant trends are described throughout this chapter and a basic interpretation of each graph is undertaken. A more precise and detailed analysis of the data takes place in the discussion.

The first part of this chapter highlights the secondary research undertaken, sourced from the World Bank. The countries used as case studies during this research include Pakistan, India, China, and Nepal. Data including population growth, GDP, energy consumption, total electric generation, and hydroelectric generation are all compared, interpreted, and described so that the changes in their relationships through time can be understood. Fluctuations in the population growth to total generation ratio are also shown through time for all four countries, as is the change in ratio between hydropower and total generation.

Following this, graphs showing the change in generation efficiency of existing hydropower developments along three South Asian Rivers are described. These include the River Indus, River Sutlej, and River Chenab. This data is plotted using line graphs and a line of best fit to make the fluctuations in the data through time and the overall change in efficiency more easily interpretable. The River Sutlej has also been used as a case study for research into fluctuations in river discharge both seasonally and annually. Data along the River Sutlej is sourced from gauging stations at Khab and Rampur and allows for an extensive understanding of the change in river discharge both in terms of volume and timing. Precipitation and air temperature graphs are also displayed here so that their influence over the rivers fluctuations can be appreciated.

The next part of this chapter looks into the dams built in India over the last century and specifically looks into how the dams being built have changed in size through time. The storage capacities of a range of dams that are located within the five states of India that border the Himalayas are also shown. This helps to show the scale of the reservoirs within the region. A graph showing how many dams have been built during certain periods is also shown, which helps interpret when the majority of development has taken place. Finally this section shows the relationship between the size of a dam and the year in which it was constructed in an attempt to examine how attitudes towards hydropower have altered through time.

The final section displays graphs showing the rate at which sedimentation is occurring in Tarbela Reservoir leading to reductions in storage capacity. This is done through the use of line graphs designed to appear as cross sections. Each graph represents a cross section from a particular location. Data has been taken from 5 different locations along the reservoir so that the build-up of sediment can be understood all along the study site rather than just behind the dam wall. Other graphs in this section show cross sections from the reservoir as a whole. Calculated predictions are also made using these cross sections regarding future bed load sediment levels.

The following sub sections interpret and describe all the figures within this chapter in a structured manner.

4.1. Population, GDP, Generation, and consumption

The relationship between these factors helps explain how energy secure a region is, a regions potential to accommodate a growing population, a countries reliance on hydropower, and the relationship between a regions economic position and its potential for power production. The data used within this section could be used to better interpret the influence each factor has over another and potentially support future issues in relation to sustainability.

4.1.1. Population growth and GDP

Figures 19, 20, 21, and 22 all show the relationship between GDP and population growth in Pakistan, India, China, and Nepal respectively. Interpreting this relationship can produce an understanding of whether population growth has encouraged GDP growth in the past or whether economic growth has first had to be achieved before a great influx of people can be accommodated. These figures also make it possible to understand how the relationship has changed through time and how it is likely to be in future years. This relationship varies between each country studied however as all accommodate starkly different economic and political environments.

Figure 19 shows the relationship between population growth and GDP in Pakistan between 1960 and 2012. Both sets of data increase exponentially through time. Population growth shows a very consistent exponential increase however GDP progressively becomes more exponential with time. Pakistan's population growth curve slightly resembles a logistic curve shown in figure 18, which is extremely common of population data.

A logistic curve shows how in theory the growth rate of a regions population will be steady at first; then growing to an exponential rate as the region experiences economic prosperity, before then slowing again as the country reaches saturation.

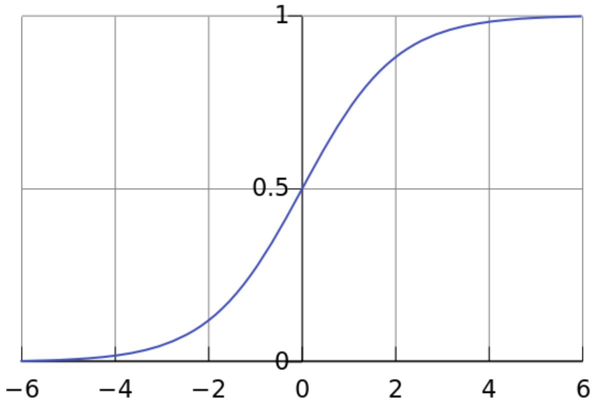


Figure 17: Logistic curve that is usually associated with population growth (Theano, 2014).

Figure 19 however shows that Pakistan's population growth curve is more sustained with a greater exponential phase than is shown in figure18 and only slight evidence that suggests population growth is beginning to slow. This shows that Pakistan's saturation point is many years in the future as it continues to accommodate a growing number of people despite pressures over space, energy, water, and poverty for example. Figure 19 also shows that Pakistan's increase in GDP is relatively slow; however a gradual increase in its rate of growth occurs up to 2000 where its growth suddenly becomes exponential. This is potentially the result of population growth creating opportunity for economic prosperity within Pakistan as industrialisation is able to occur more rapidly. Increases in the rate of GDP growth is expected however, despite poverty, as a percentage of the population in Pakistan has become far wealthier over recent years as a result of economic opportunity.

Growth in GDP has been consistently positive over the past 15 years, excluding one anomaly in 2009. The correlation realised in figure 19 indicates that as Pakistan's population has grown consistently, this has helped initiate a more exponential growth in GDP. This looks set to continue; however it is likely that whilst population growth has helped encourage economic development, economic saturation as a result of limiting energy and water resources is set to slow population growth in the future.

This relationship is very similar in figure 20 which shows data from India. Population growth is even more exponential and sustained in India with no resemblance to a logistic curve at all. The growth in GDP however is very similar to that shown in Pakistan with a similar anomaly occurring in 2008. This is possibly because both countries share relatively similar economic and political contexts. India's growth in GDP is relatively slow during a lag phase that exists from 1971 to 2003 where there is a sudden increase in GDP growth. This is again potentially the result of population growth initiating opportunity for economic expansion. As with the previous figure, a growth in the population has led to an increase in average income and a resultant increase in economic development.

Figure 21 shows the same relationship in China. Population growth in China has been exponential over the past 50 years. China was the first country in Asia to really develop and expand. As a result, there are now signs of saturation in relation to the regions rate of population growth. Since 1995 the rate of population growth in China has reduced. China growth curve shows the strongest resemblance to figure 18 compared with the other countries studied. This is potentially the result of China falling into stage 4 of the demographic transition model. It will also be a partial result of the one child policy introduced in 1979 to alleviate social, economic, and environmental problems. GDP growth in China has also occurred at a greater rate than in any country researched in this section. This is only the case after 1995 however. Prior to this GDP levels remained relatively stationary during its lag phase. This is probably the result of its large population that lives below the poverty line keeping GDP levels low. GDP has however doubled in the last 10 years in China and current trends suggest this is set to continue.

Figure 22 shows the relationship between population growth and GDP in Nepal. It would be predicted that the correlation shown in this figure would be different to that shown in the previous three due to Nepal's dissimilar economic and political context. Nepal still accommodates a largely traditional economy that is looking to develop into a more prosperous commercial one. Here the population curve more closely correlates with that shown in figure 18. This is potentially because Nepal's capacity for population growth is smaller thanks to a simple lack of space and more hostile local environments. As a result its capacity to accommodate a population will be reached more quickly. GDP however follows a more similar trend to those shown in figures 19 and 20, however obviously the GDP values are significantly smaller. There is a gradual increase in GDP growth until roughly 2003 where more exponential growth suddenly occurs. It again appears from this figure that the growth in GDP has been encouraged by population growth.

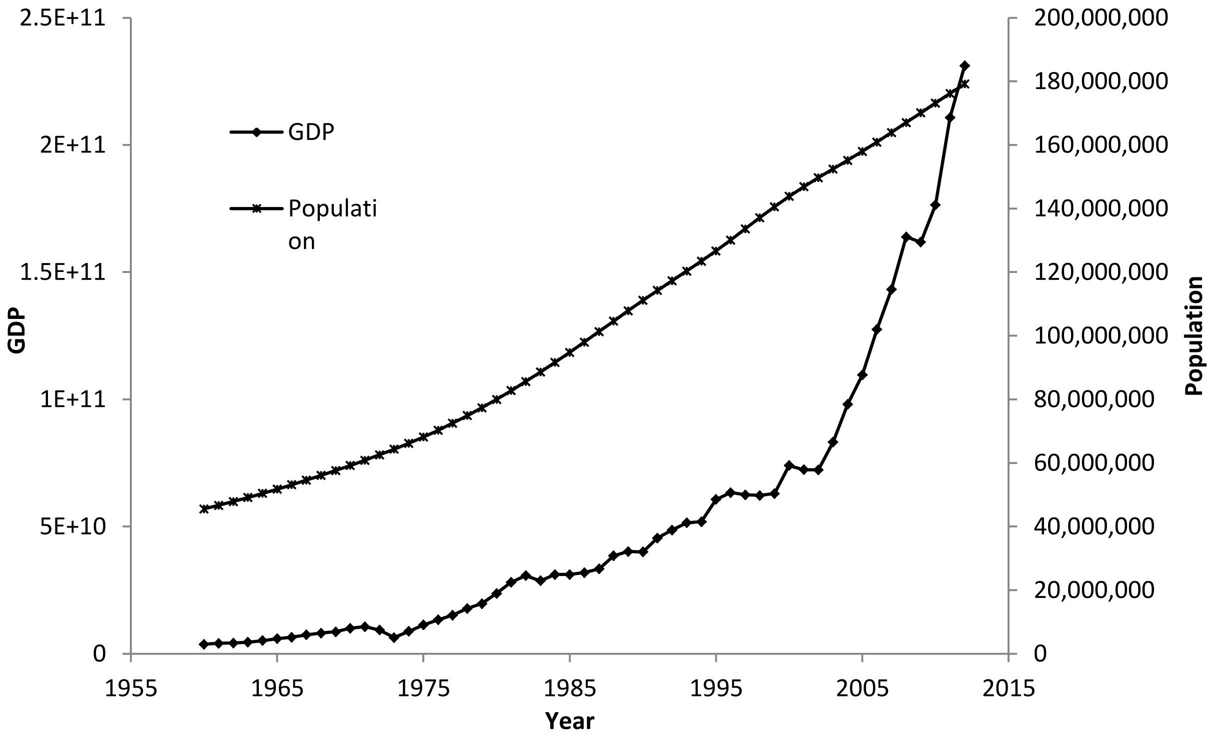


Figure 18: The relationship between population growth and GDP in Pakistan.

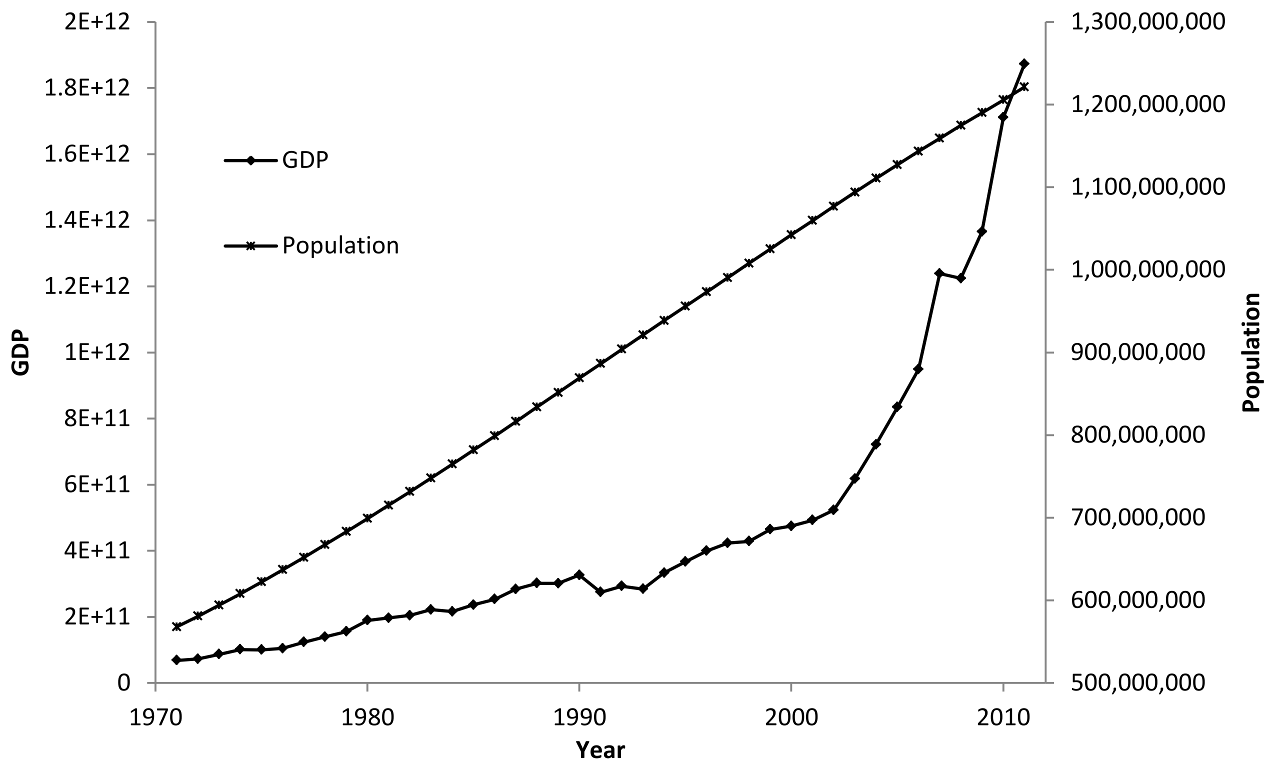


Figure 19: The relationship between population growth and GDP in India.

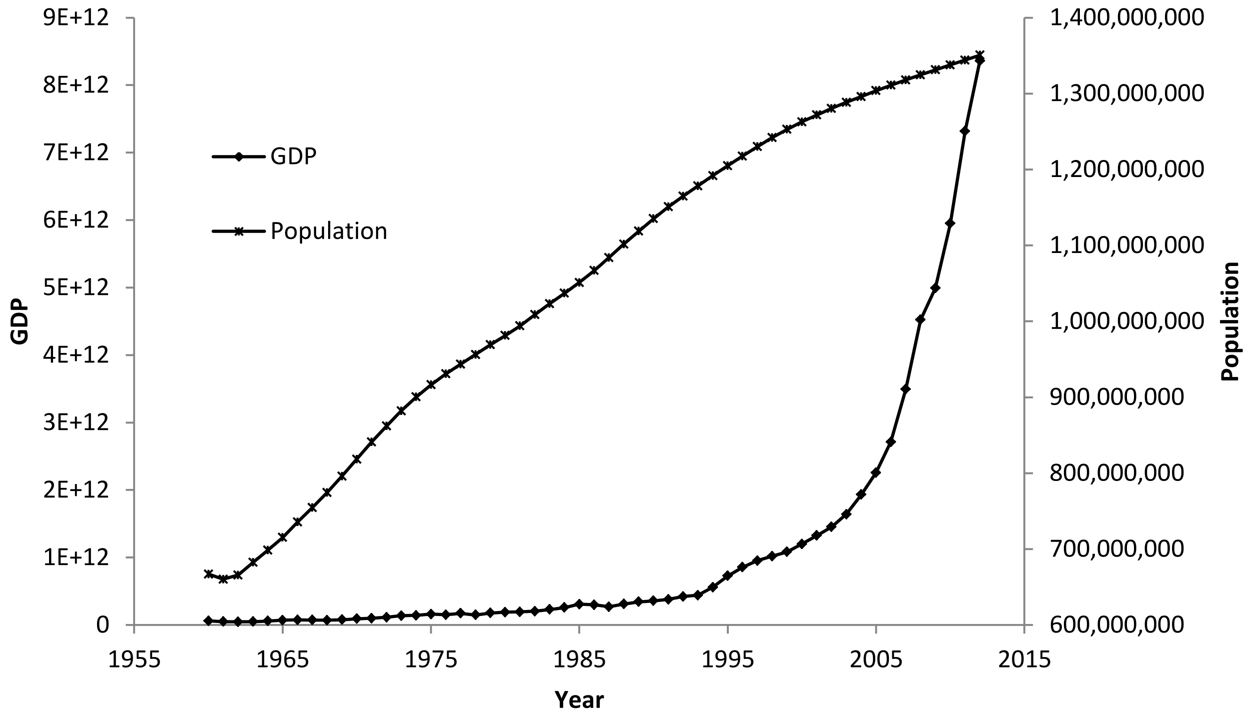


Figure 21: The relationship between population growth and GDP in China.

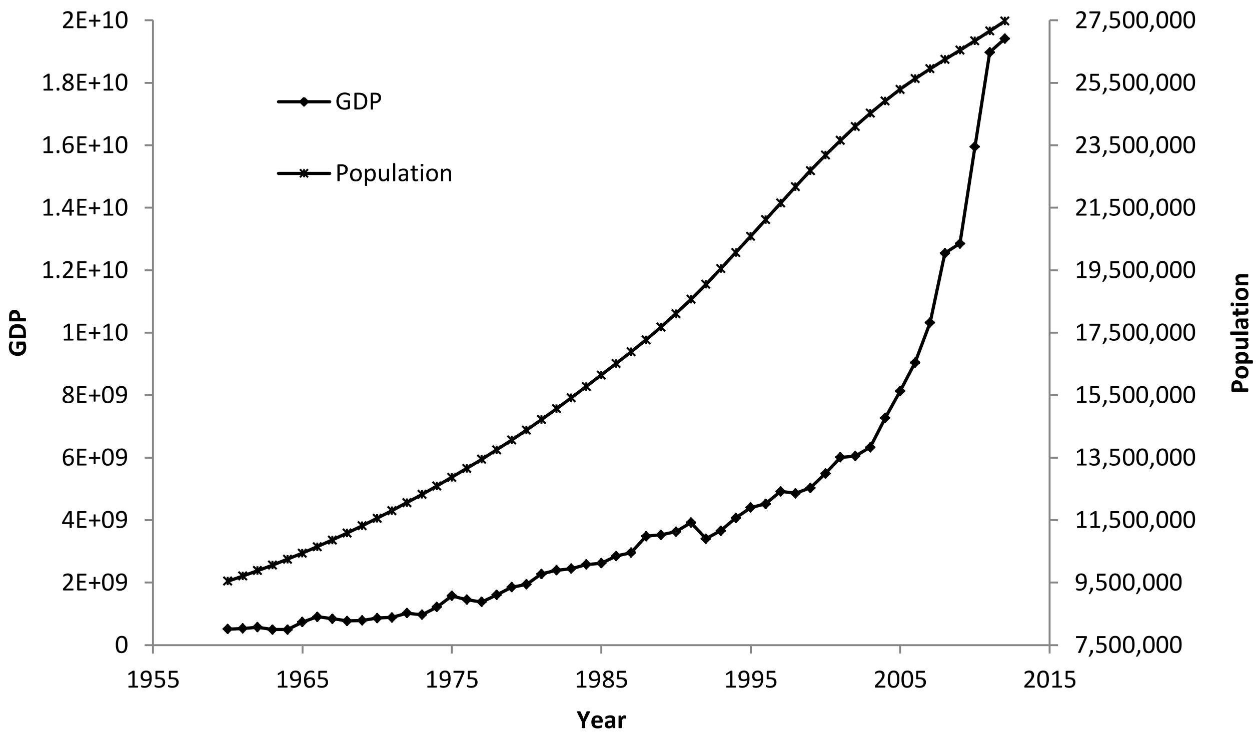


Figure 20: The relationship between population growth and GDP in Nepal.

4.1.2. Population growth, generation, and consumption

The following figures show the relationship between population growth, hydroelectric generation, total generation, and a countries total electricity consumption. There are a range of relationships to interpret here. The relationship between population growth and generation is important as it is essential for a regions continued economic growth for energy supply to meet demand. It can also be seen in the following figures whether over the past 40 years each country is supplying enough energy to meet its growing demands. The relationship between total generation and hydroelectric generation can also be seen in the following figures. This is an important relationship to interpret as it helps explain how dependent a country is on hydroelectric power. This can help determine how energy secure a region is. Countries can become extremely energy insecure if they do not have the capital available to diversify their energy supplies.

Figure 23 shows these relationships in Pakistan from 1971 to 2012. This figure shows a strong positive correlation between population growth and generation. As the population has grown, total generation has also grown to match the growth in demand. The generation curve however shows far more fluctuation than the population curve. The graph also shows that population growth is occurring at a faster rate than generation growth which could potentially cause problems as shortfalls in demand begin to become more greatly realised in later years. This is particularly the case as generation falls in 2007 with only a slight recovery in 2009. It could be understood that populations grow exponentially, whilst generation supply can only increase arithmetically.

From figure 23 you can also see that consumption correlates strongly with total generation. Generation in Pakistan however slightly outweighs consumption which is highly beneficial in terms of reducing the need for imports. This also creates economic opportunity for Pakistan as it produces an oversupply of energy that can be sold to neighbouring regions. The decrease in generation in 2007 however is followed by a reduction in consumption in 2008. This is potentially the result of falls in generation reducing the country's ability to consume energy as the resources are not available. This occurs because both data sets are so similar to one another making fluctuation's in Pakistan's generation critical to its consumption capabilities. The difference between demand and supply has grown gradually however over the past 40 years. This both reduces pressures over ensuring a consistent supply of energy and increases the countries surplus to potential export. This is potentially unexpected in light of increasing demand and concerns over reserves and pricing.

Hydroelectric generation in Pakistan is also increasing; however there are many fluctuations within the data. This is concerning as an inconsistent supply of renewable energy can cause problems in relation to meeting more consistent demand. Fluctuations in this data also increase from 1992 which shows the supply of hydroelectric power is becoming more inconsistent and potentially more vulnerable despite increases in production. The difference between total generation and hydroelectric generation is however significant which shows Pakistan's reliance on hydropower is minor. The rate at which hydroelectric production is increasing is also far less than that of population growth and total generation. This shows that despite increasing investment into the renewable source, its significance within total production has decreased since 1970.

Figure 24 shows the relationship between population, generation, and consumption in India. There is again a strong correlation between population growth and total generation. The rate of total generation growth increases in an attempt to match the exponential growth in population. There are far less fluctuations in the generation data compared with that of Pakistan's. Fluctuations here are far less significant, reducing risk. The rate of generation growth surpasses that of population growth in approximately 2002. This is highly beneficial as it proves India has the resources at present to accommodate growing demand for energy. Like in Pakistan, electricity generation in India outweighs that of consumption. This is highly beneficial in terms of economic development as foreign investment is minimal and potential for income is realised. The difference between generation and consumption also increases through time which means India's surplus of energy is also growing annually.

Hydroelectric generation has also increased from 1971; however it only represents a tiny proportion of the total electricity generated by India. It is far less significant than in Pakistan for example. This shows that India's reliance on hydropower is exceptionally minuet. This also suggests however that the majority of India's supply is still sourced from non-renewable sources. Fluctuations in the hydroelectric generation data also increase from roughly 1994. This potentially indicates that externalities are causing production and reliability issues for the energy source. Hydroelectric generation is not increasing at anywhere near the rate that would be necessary for it to be a significant source of supply in India. In 2011, hydroelectric generation only made up 12.4% of total generated power in India. It could be argued however that this is significant given the similarity between production and consumption. In 2011 total consumption was only 21% less than total generated output.

Figure 25 shows the same relationship in China from 1971 to 2012. Total generation of electricity is gradual until roughly 1999 when growth becomes exponential. This is potentially supply reacting to population growth as demand for energy has soared. There are also few fluctuations shown in this generation data showing a far more consistent supply of energy compared with both Pakistan and India. Despite population growth rates decreasing there are however no signs of reductions in the rate of generation growth. This shows that per capita demand has increased over recent years in China as the quality of life has improved. Again for China, electricity generation outweighs consumption; however Chinas surplus is far smaller than those shown for the previous two countries. China consumes almost all its generated electricity. This is shown by the consumption and generation data sets following one another almost exactly. This demonstrates a high level of efficiency from Chinas energy sector. As both production and consumption have grown, the difference between them has also grown. This change is extremely minor however, particularly in comparison to the change seen in the previous two cases.

There is again a large difference between total generation and hydroelectric generation for China. This is beneficial in terms of diversity; however this indicates that a large percentage of Chinas generation comes from other more polluting sources. The rate of hydroelectric generation growth increases after 2000. This increase is insignificant in comparison to overall growth rates and consumption however. The difference between total generation and hydroelectric output is now the greatest it's ever been despite huge scale investment into the renewable source. In China in 1971 hydropower made up 21.67% of total generation. In 2011 however, hydropower input fell to just 14.7%. This demonstrates how other sources of generation are expanding at a faster rate than hydropower is, despite growing interest towards the power source.

Figure 26 shows the same relationship in Nepal from 1971 to 2012. Here the results are very different to those shown in the previous three figures, particularly when analysing hydropower generation in Nepal. Up to 1998 the rate of generation growth is less than that of population growth. After this however the rate of generation increases to more than match that of the population rate. This is encouraged by a slowing population growth rate. Population and generation values in Nepal are obviously far smaller than those shown in the previous three case studies. There are also very few fluctuations in the total generation data for Nepal apart from a brief period between 1988 and 1997. Here a consistent increase in the data is interrupted by minor fluctuations that may have caused supply issues. Consumption in Nepal also correlates very closely with generation. Importantly however consumption is less than generation here meaning they have a surplus of supply. This is particularly beneficial for Nepal as it doesn't have the capital accessible to source energy from elsewhere. The surplus has also grown over recent years so they now have a greater level of supply left as surplus after they have met demand. This represents potential for profit making.

The correlation between total generation and hydroelectric generation is extremely interesting in Nepal. Both curves follow each other almost perfectly. This shows that Nepal relies almost completely on hydropower for it energy supply. This is highly beneficial in terms of its carbon footprint and environmental impact. It is potentially dangerous however as hydropower becomes theoretically unsustainable. Relying almost completely on one source of power encourages energy security issues. This is because it severely reduces a countries capacity to source alternatively. The greatest difference between both total and hydropower generation occurs between 1990 and 2000 where fluctuations in hydropower are at their greatest. This potentially indicates that as the supply of hydropower becomes more inconsistent, Nepal relies more heavily on alternative sources.

Figure 27 shows the population/generation ratio for all four countries researched in this section. It is clear from figure 27 that for all countries the generation per person is falling. The rate at which this occurs however gradually slows through time. The ratio for Pakistan for example begins to slightly increase after 2006 which would indicate either a reduction in the population growth rate or an increase in the generation of electricity. Nepal shows the greatest fluctuation from 1971 to 1976; however after this the ratio falls similarly with the other three countries. It is important to mention that Nepal has by far the highest ratio compared with the others with its highest ratio figure being 14.6 compared with India's for example being 0.85. This shows that Nepal generates far more energy per capita than the other three countries. This is due however to Nepal having a comparatively tiny population compared to the others and also having the greatest natural resources for energy production. Finally figure 27 shows that despite exponential increases in the generation of electricity, it is still not keeping up with increases in population and growing demands per capita.

Figure 27 shows the hydropower/total generation ratio in all four countries researched in this section. This ratio indicates how reliant a country is on hydropower as a source of electricity and how this reliance has changed through time. It is clear from figure 27 that Nepal's reliance is far superior to that of the other three countries. Nepal is now almost 100% reliant on hydropower, increasing from 77.9% in 1971 to 99.9% in 2012. This is vastly different for India and Pakistan however. Both ratios reduce at similar rates; however Pakistan's reliance stays higher than India's throughout. Both India's and Pakistan's hydropower/total generation ratio's reduce by roughly 20% over the 41 year period. China however shows the smallest reduction by far. This will be partly the result of China having the majority of the power in the region in terms of dam building and river development. It does however have the lowest overall ratio of hydropower/total generation on average. This is because Chinas energy demands are so high that hydropower can only represent a small proportion of production despite recent developments. Even though hydropower is becoming an increasingly exploited resource in South Asia, it is clear that other resources are having to be increasingly utilised to meet demand.

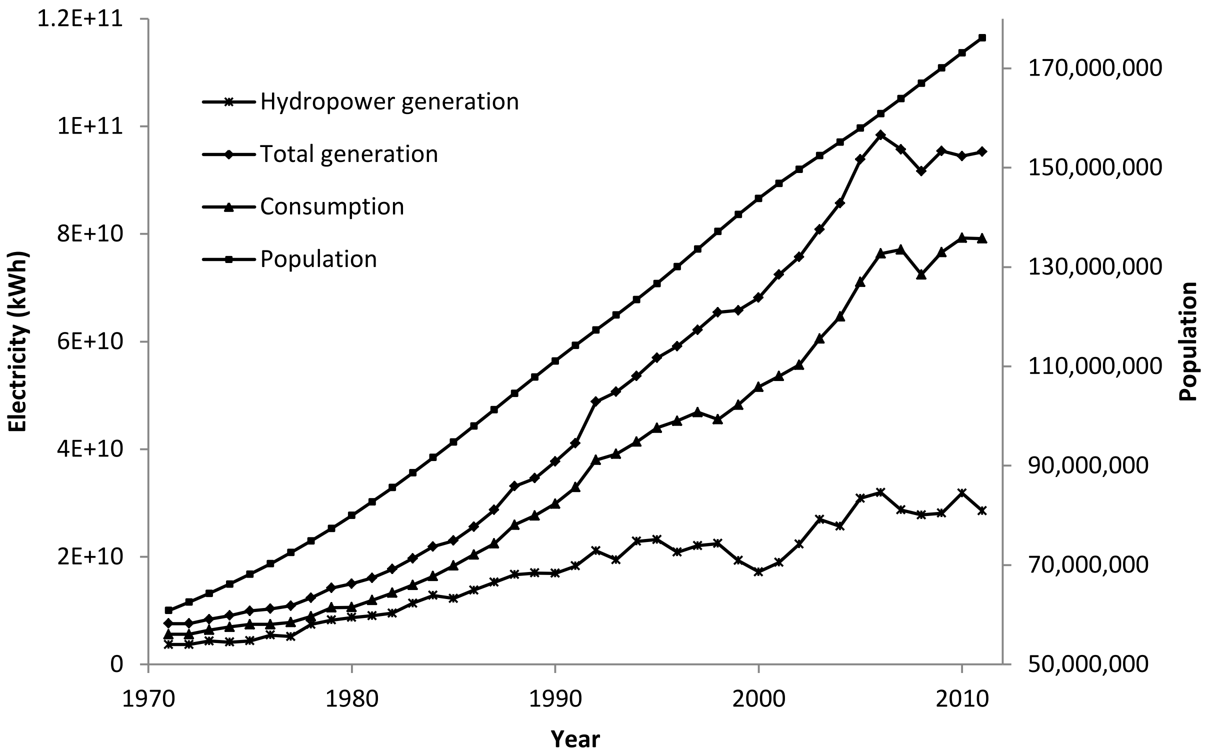


Figure 22: Relationship between population growth, total generation, hydropower, and consumption in Pakistan.

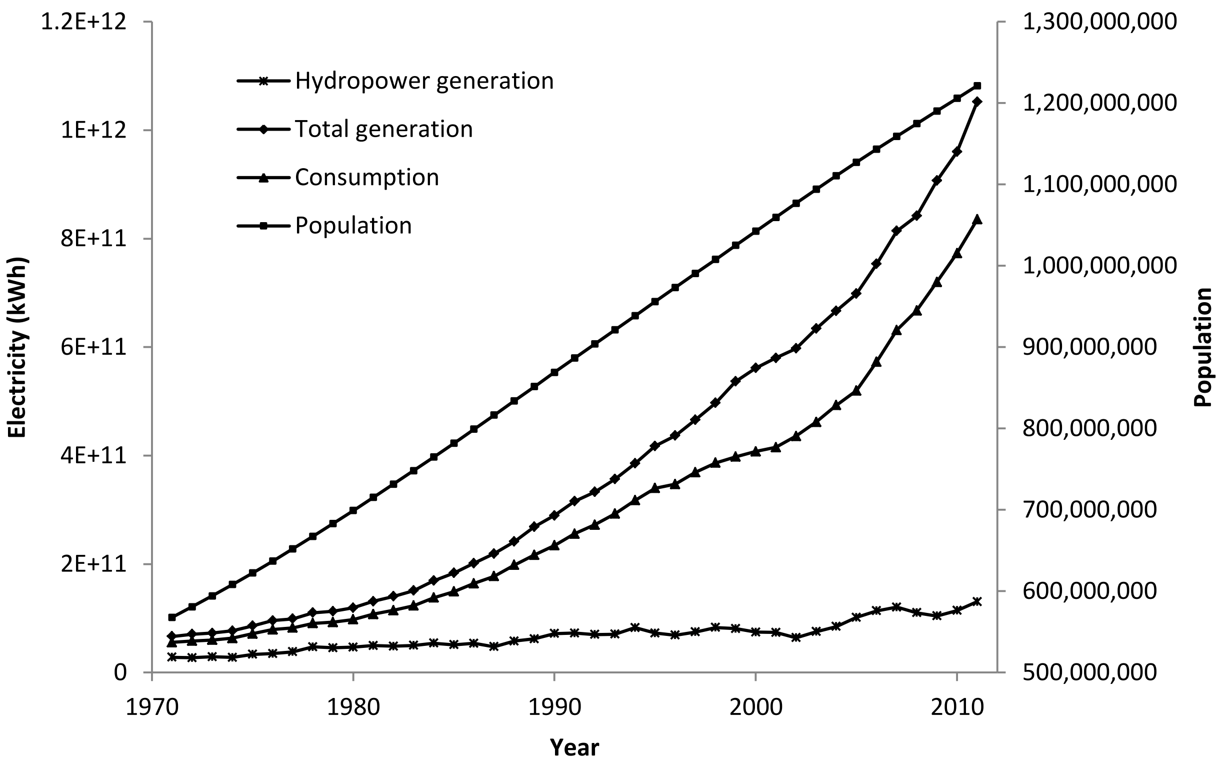


Figure 23: Relationship between population growth, total generation, hydropower, and consumption in India.

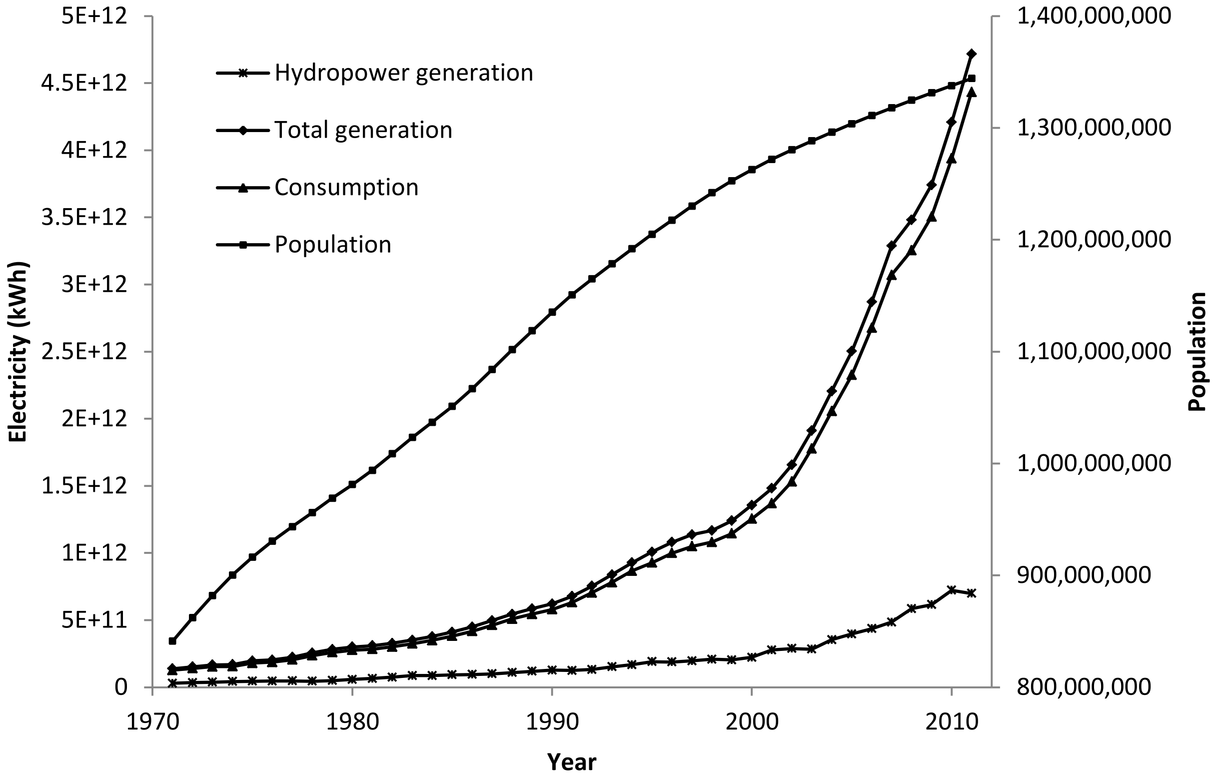


Figure 24: Relationship between population growth, total generation, hydropower, and consumption in China.

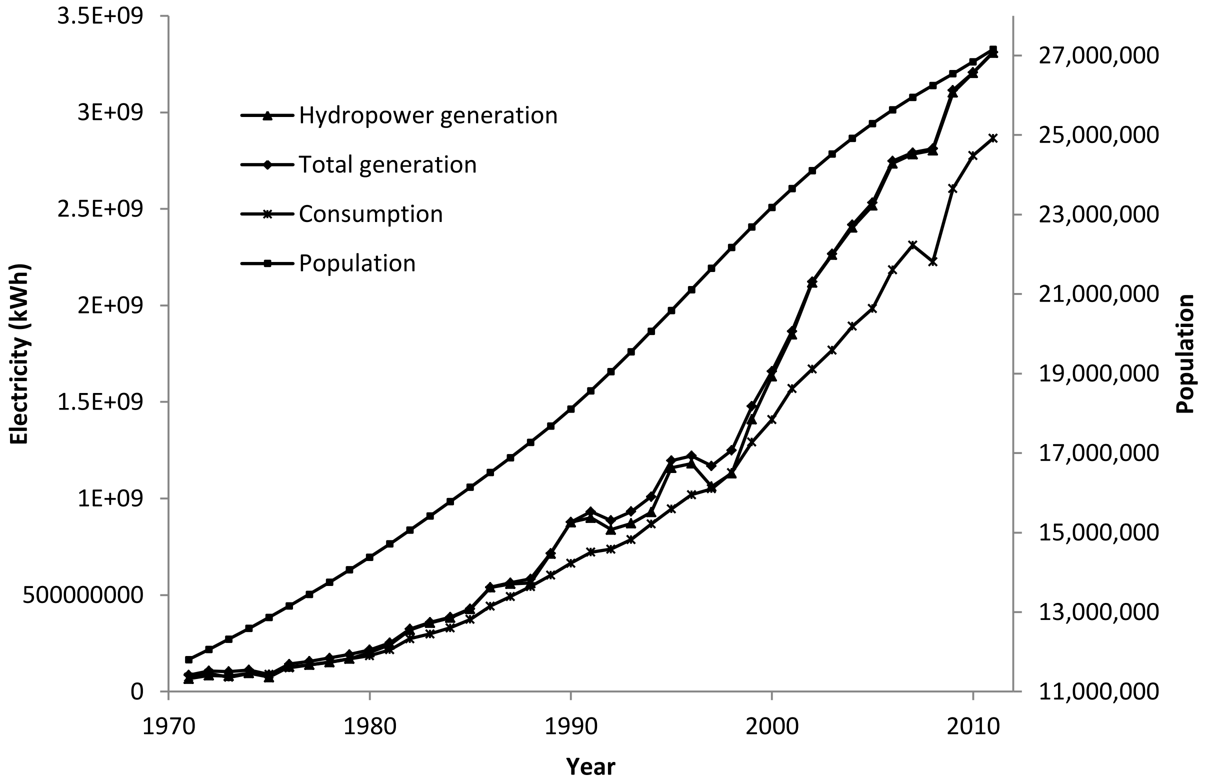


Figure 25: Relationship between population growth, total generation, hydropower, and consumption in Nepal.

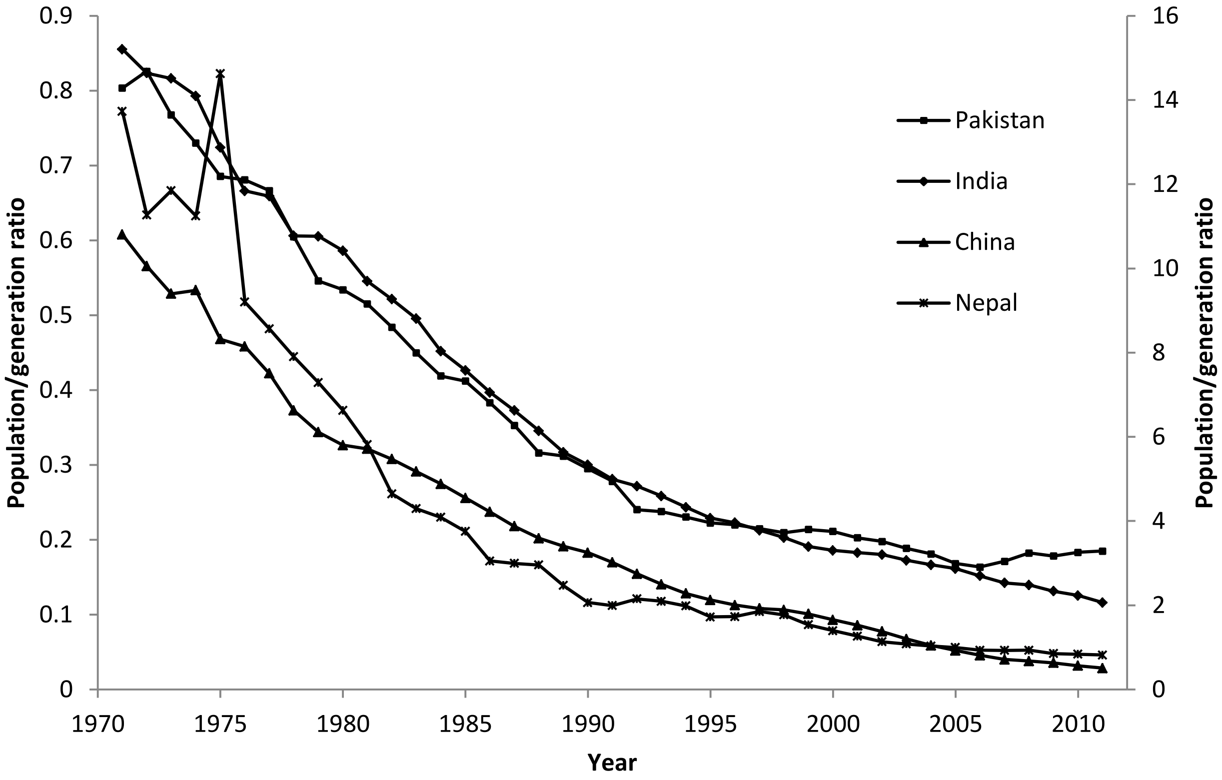


Figure 26: Population to electricity generation ration in Pakistan, India, China, and Nepal from 1971 to 2012.

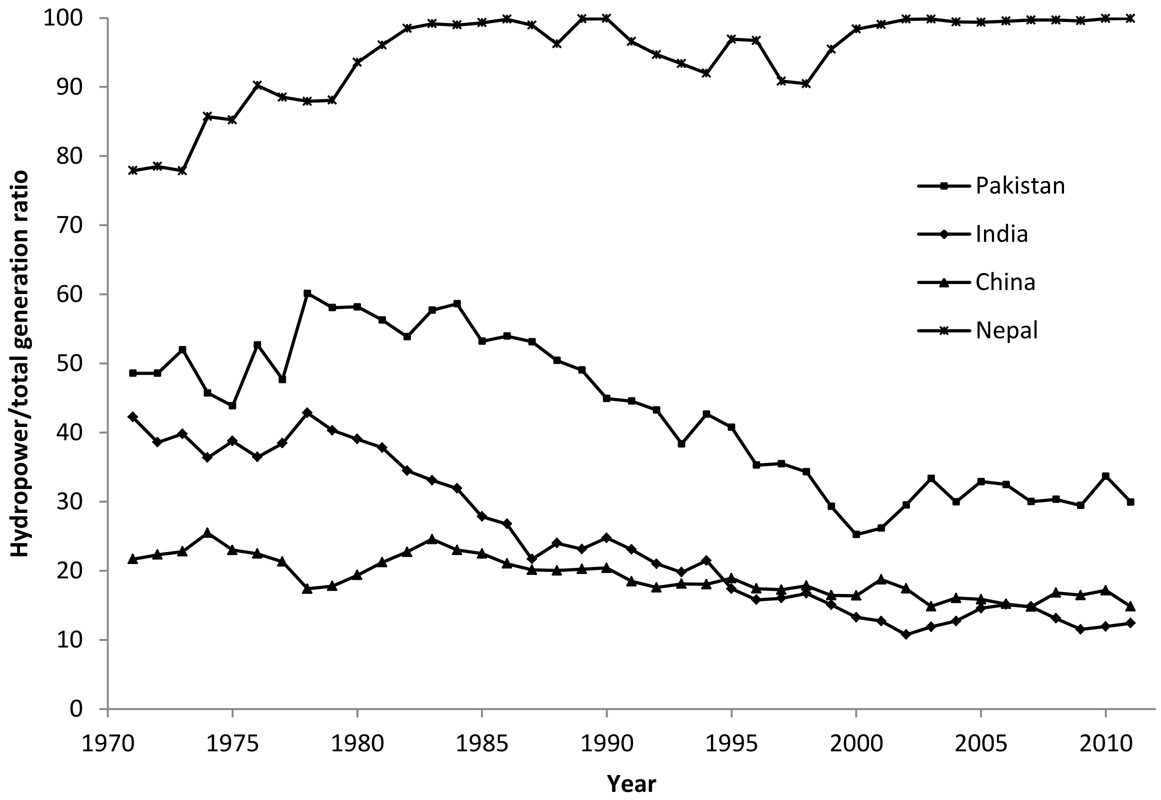


Figure 27: Hydropower/total generation ratio of Pakistan, India, China, and Nepal from 1971 to 2012

4.1.3. GDP and hydropower

The following figures show the relationship between GDP and hydropower. This relationship encourages the understanding of how a countries economic development and its production of hydroelectric power are related. Theory states that access to energy is the main fuel behind economic growth. Understanding this relationship can help in understanding the importance of hydropower in certain regions and its potential to encourage further economic prosperity.

Figure 29 shows the relationship between GDP and hydroelectric generation in Pakistan from 1971 to 2012. GDP and hydropower are relatively well correlated in figure 29 as both increase at a similar rate through time. Between 1971 and 1995 the growth in hydroelectric generation is relatively consistent. Between 1971 and 2002 this is also the case for the growth in GDP. After this however generation begins to fluctuate more severely, yet the rate of growth remains similar. This potentially indicates that hydropower is becoming an increasingly unreliable resource that is suffering more and more from inconsistencies in supply. GDP growth however increases to even more exponential levels after 2002 ignoring an anomaly in 2008. GDP is continuing to grow at an exponential rate whilst the rate of hydropower growth remains similar. This potentially indicates that GDP is being influenced far more by other sources.

Figure 30 shows the same relationship in India. Correlation here is very similar to that shown in Pakistan. Hydropower however shows a far greater scale of fluctuation with greater fluctuation occurring after 2002. The rate of hydropower growth also increases after 2002 which correlates directly with a sudden increase in GDP growth rate. In figure 30 it appears that hydropower has a greater influence over economic growth than in the previous figure. GDP growth is exponential after 2002 in India; however there is an anomaly in 2007, one year prior to the anomaly recognised in figure 29. The greatest increase in hydroelectric generation in India occurs between 2002 and 2007 where generation almost doubles over five years. This is potentially the result of a large development in India and could also have been encouraged by increases in river discharge, dramatically increasing hydroelectric productivity. The period of time in which hydroelectric generation growth increases mirrors that of increases in GDP growth. As a result it could be argued that either greater generation has encouraged GDP increases, or economic expansion has led to a greater ability to produce hydropower. It is difficult to accurately interpret the answer to this just through the analysis of figure 35 however.

Figure 31 shows this relationship in China from 1971 to 2012. The correlation shown in this figure is by far the strongest witnessed out of all the figures in this section. Both data sets strongly resemble J shaped curves as in the first few years of data they increase slowly and then suddenly increase to exponential rates of growth during following years. There is also little fluctuation at all in both curves and no anomalies of data. This potentially indicates then that hydropower is having a positive impact on economic development in China and is contributing strongly to the regions wealth. This relationship however could also be purely coincidence. This is encouraged by figure 28 which shows that China has the weakest hydropower/total generation ratio and is fuelled far more strongly by alternate sources of energy. This indicates its impact on the economy should be the smallest out of all the case studies. Figure 31 however does demonstrate that in China economic expansion closely relates to energy production, supporting the theory that energy is essential for growth.

Figure 32 shows the same relationship in Nepal. Both GDP and hydroelectric generation again have a strong correlation with both increasing sharply. Both GDP and generation levels are far smaller in Nepal than in Pakistan, India, and China. Hydroelectric generation in Nepal is also growing at a faster rate than GDP, which is dissimilar to what has been recognised in the previous three figures. This is because Nepal has huge hydropower potential however is still relatively poor economically, particularly in comparison to India and China. Hydropower growth begins to increase after 1988 in Nepal; however GDP growth starts to increase later in 2002. Correlation here indicates that the development of hydropower has encouraged economic growth in Nepal. This would be expected as hydropower represents Nepal's greatest asset in terms of generating income. GDP growth looks to continue to increase in figure 32; however the rate at which hydroelectric generation is growing looks to be slowing.

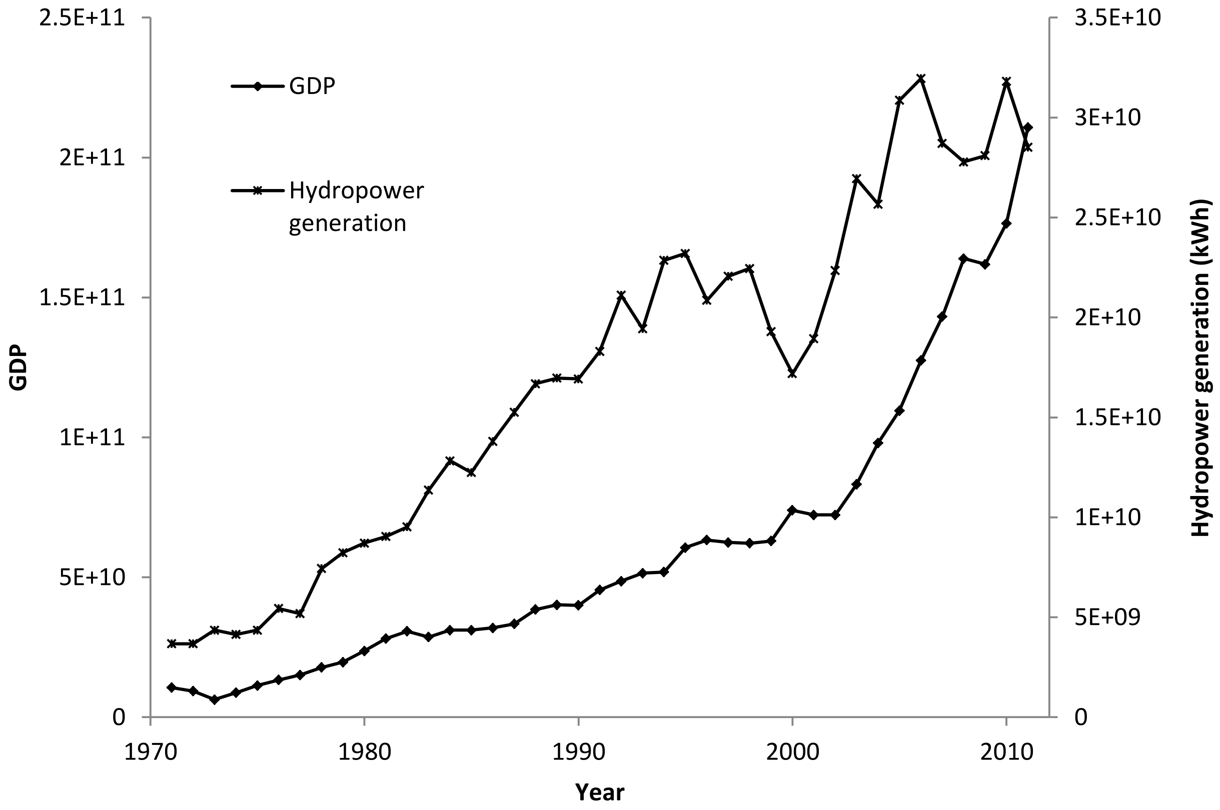


Figure 28: The relationship between GDP and hydropower generation in Pakistan.

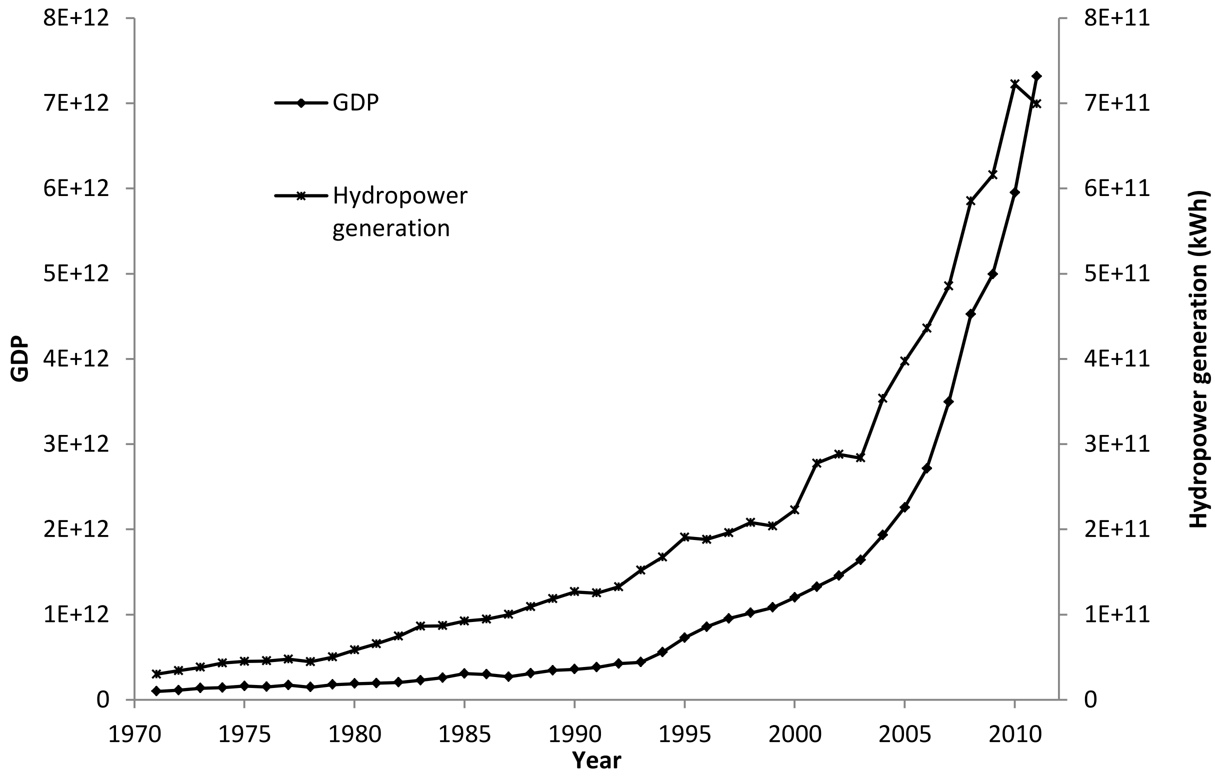


Figure 29: The relationship between GDP and hydropower generation in India.

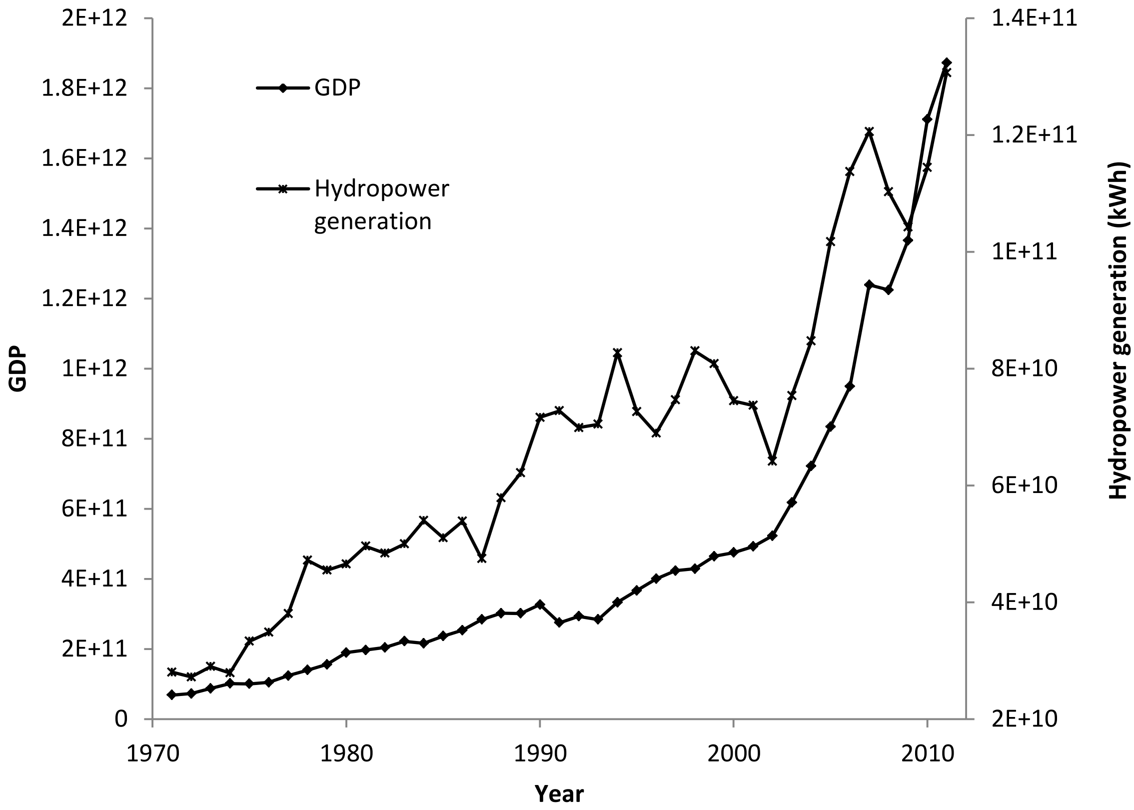


Figure 30: The relationship between GDP and hydropower generation in China.

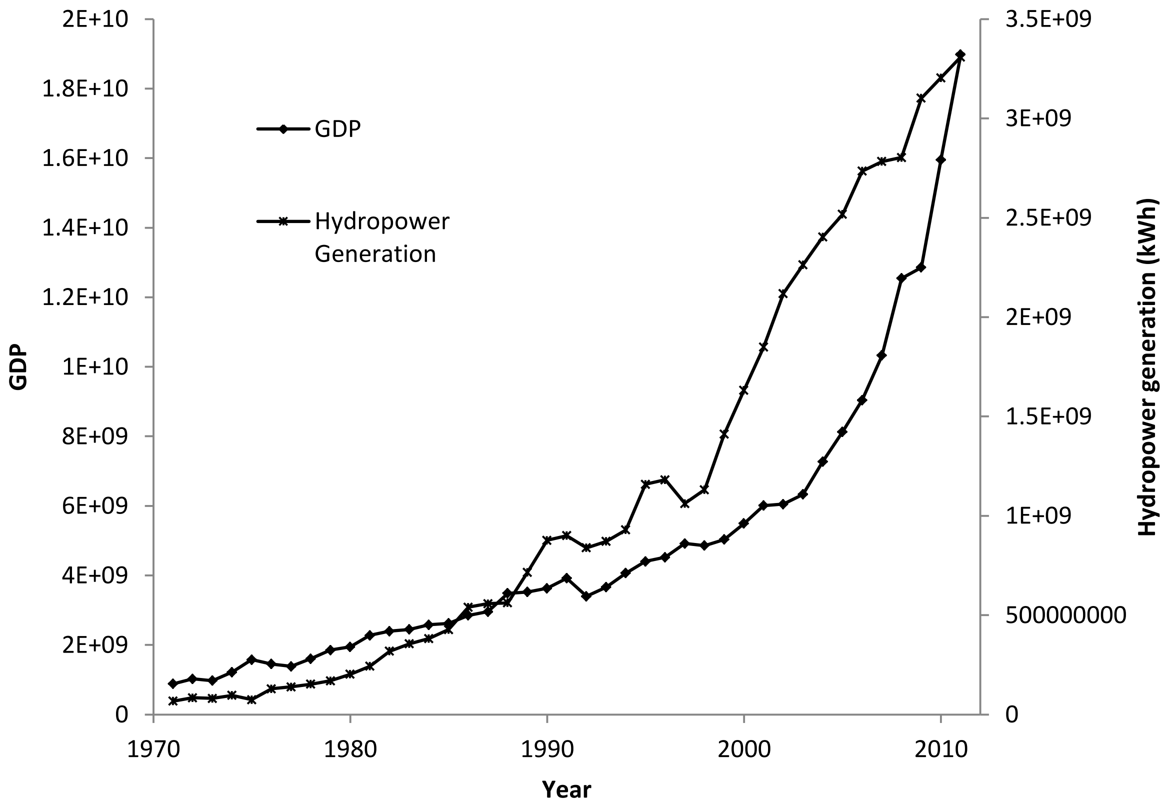


Figure 31: The relationship between GDP and hydropower generation in Nepal.

4.2. Existing hydropower generation efficiency

Figures 33, 34, and 35 show the efficiency of existing hydropower infrastructure along the river Sutlej, river Chenab, and river Indus respectively. Understanding how the efficiency of hydropower has changed through time is beneficial in terms of estimating the feasibility of future investment and the potential future need for mitigation. Included in all three graphs is a line of best fit which helps to more easily interpret how efficiency has altered. Efficiency is an accurate measure of feasibility. If existing projects are now generating less electricity than they were originally then they have become less financially viable as the payback time on the project begins to extend. This is crucial information for political leaders who may be looking to increase the capacity of generation along river systems that now have different generation capacities compared with what was originally understood.

Figure 33 shows a high level of fluctuation in the generation performance along the river Sutlej. This immediately demonstrates the hostility of hydropower as an energy source. Overall generation from 1986 to 2013 falls from 4.35 to 4.19 MU/MW. The overall efficiency of existing developments along the river Sutlej has therefore fallen. The greatest generation output occurred in 1999 (6.08 MU/MW) whilst the lowest occurred six years later in 2005 (3.44 MU/MW). This is almost a halve in generation in just six years. This shows that hydropower along this catchment is both a volatile and unpredictable source of energy as well as one that is reducing fairly rapidly. This is concerning in relation to electricity supply as it must continue to meet demand which is recognised as a significantly more constant data set, and one that is also increasing. The River Sutlej is also one of the most developed river systems in South Asia and has one of the greatest hydropower potentials. This makes this fall in generation particularly concerning in relation to future generation prospects as a greater level of development will have to occur just to maintain a certain level of output.

Figure 34 shows that hydroelectric generation along the river Chenab from existing sources has also reduced overall. The pattern of the data shown in this figure is far different to that shown in figure 33 however. Generation reduces significantly from 1991 (6.23 MU/MW) to 1995 (2.85 MU/MW), whereby it is more than halves. This reduction in generation is substantial in a very short space of time. Generation then steadily increases from 1995 to present, however it has not yet recovered to its original level of generation realised in 1991. Fluctuations in figure 34 are also far less volatile than those shown in figure 33. Reasons for the increase in generation from 1995 may include an increase in hydroelectric installation, increase in runoff, improved dam maintenance, dam expansion, reduced silting etc. It is clear from figure 34 however that a strategy for recovery was needed after the dramatic fall in generation.

Figure 35 also shows that generation along the river Indus has reduced. This figure is very similar to figure 33 in relation to the pattern of data and the fluctuations recorded. This is expected however as the River Sutlej is one of the River Indus's major tributaries, meaning they share similar river properties and climates. The reduction in hydroelectric generation on the River Indus is however not as sharp as that shown in figure 33. This is potentially the result of development along this catchment being less dense in comparison. The greatest generation recorded occurred in 1999 (5.2 MU/MW) whilst the lowest occurred in 2005 (3.54 MU/MW). The years in which the minimum and maximum values occur match those shown in figure 33. The differences between them however, in terms of generation, are not as great. The fluctuations and overall reduction in generation shown along the River Indus is particularly concerning for the feasibility of dams such as Tarbela, which represents a hugely important resource in Pakistan. It is clear then that mitigation strategies will be needed to improve the efficiency of current hydropower developments, before potentially further uneconomic investments occur.

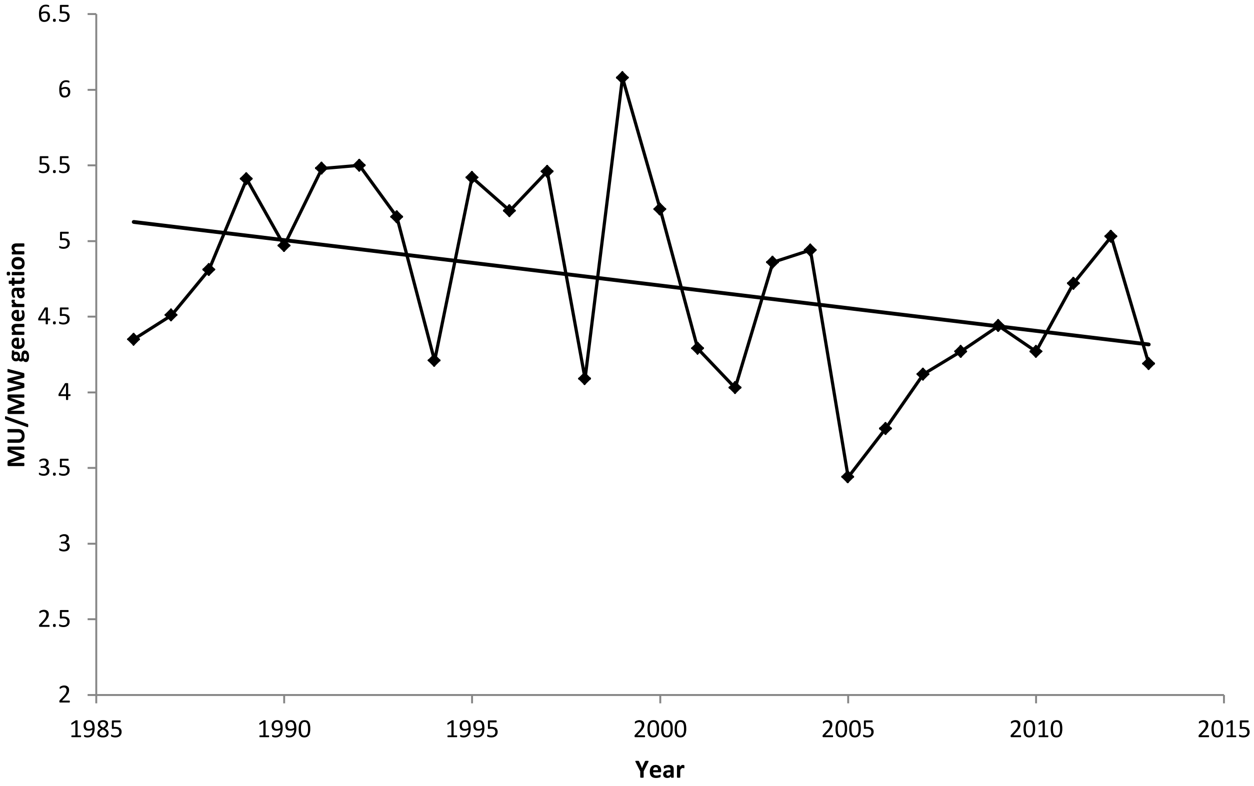


Figure 32: Hydropower performance from existing stations within the Sutlej river basin.

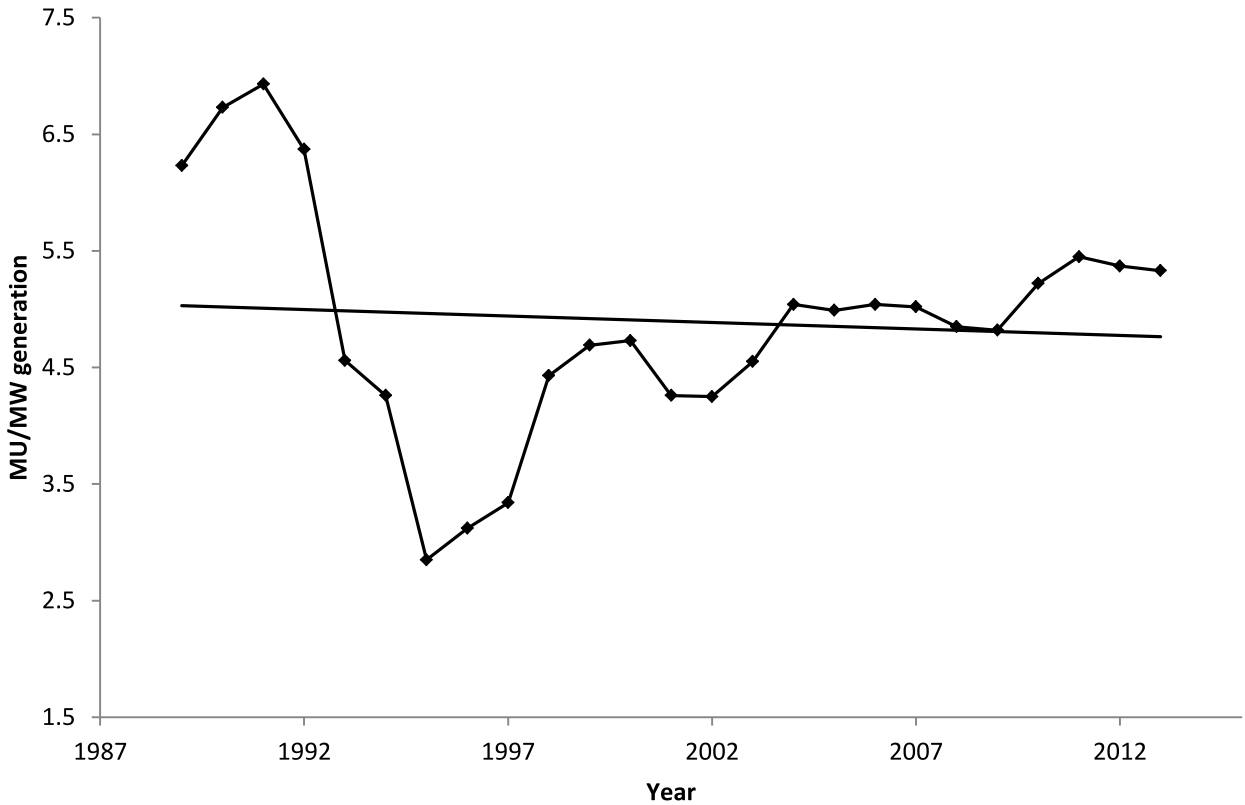


Figure 33: Hydropower performance from existing stations within the River Chenab basin.

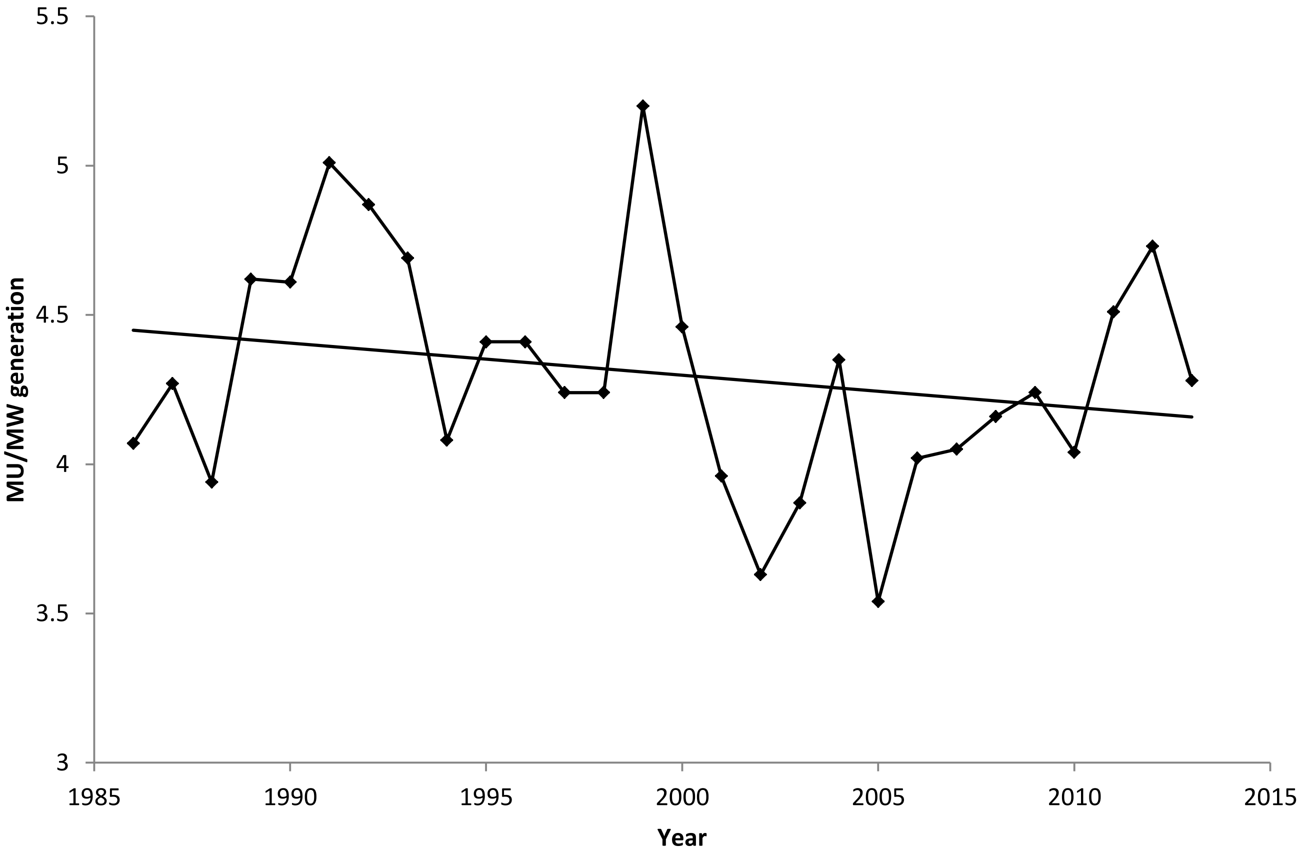


Figure 34: Hydropower performance from existing stations within the Indus river basin.

4.3. River Discharge and hydro-meteorological change

The following figures show how the magnitude and timing of river discharge has changed in the River Sutlej at two different gauging stations. Khab and Rampur are both gauging stations situated along the river Sutlej. This enables comparisons to be made along the river between discharge data and gives more depth to the overall research. River discharge is crucial to understand as hydroelectric generation is directly related to river runoff. The change in timing of peak discharge is also important as this could encourage shortfalls in supply during certain months or wasteful production during others. Patterns of discharge could also be analysed to help predict future levels of discharge and change in timing and magnitude to help interpret whether future investment into hydropower could be economically feasible.

Figures 36 and 37 show the change in annual discharge and the change in timing of the peak river discharge at Khab gauging station on the River Sutlej respectively. In figure 36 the maximum river discharge occurs in 1973 whilst the minimum discharge occurs in 2001. This is a substantial fall in discharge with the difference between the two values being roughly 8000 ($10^6 m^3$). This difference in discharge is massively significant, particularly as this difference represents 80% of the maximum discharge achieved in 1973. Up to 1996 overall runoff is kept at relatively constant level despite fluctuations. After this however discharge noticeably reduces. Due to the high frequency and magnitude of fluctuations it is very difficult to predict from figure 36 how levels of runoff are due to change in future years. It is obvious however that the runoff supplying the basins hydroelectric generation is reducing. The timing of this discharge has also changed to potentially cause issues in relation to supply. Figure 37 shows that during 1973 when the greatest annual recorded river discharge was realised, maximum runoff occurred during June. In 2001 however, when the minimum level of runoff was recorded, maximum runoff occurs a month later in July. It is also clear that the greatest change between both years occurs during the summer months when discharge is at its greatest. During the winter months however whilst discharge is at its lowest, the difference between both years is minor in comparison.

The same comparisons are made relating to Rampur gauging station which lies further downstream of the rivers source. Figure 38 which shows the change in annual runoff from 1964 to 2005 is very similar to that of figure 36. Maximum and minimum discharge occur in 1973 and 2004 respectively, which is extremely similar to that found at Khab. The difference between these two points is roughly 10,000 ($10^6 m^3$). This again represents a huge percentage loss in discharge. It is predicted that this difference would be larger than at Khab however because of the stations more downstream location. A greater number of tributaries have influenced the flow at this point meaning discharge and overall change will be greater. As a result this location is affected by a greater magnitude of externalities. Fluctuations are also extremely high which threatens the rivers potential for a consistent supply of electricity. Figure 39 is also extremely similar to figure 37. During 1973 when the greatest level of discharge was realised, maximum discharge occurred in June. In 2004 however when the smallest annual runoff occurs, maximum discharge occurs in July. At both stations, the greatest variation in discharge occurs in June, whilst the smallest occurs in January, February, and March. Figures 37 and 39 show very clearly how reliant the region is on a strong supply of water between April and September as winter discharge is comparably insignificant.

Figures 40 and 41 show changes in precipitation and average air temperature levels respectively along the river Sutlej basin. Comparing these figures with the river discharge data is important in understanding the significance of hydro-meteorological conditions on Himalayan river runoff. It is clear from figure 40 that precipitation levels have remained constant despite high levels of fluctuation ranging from a maximum in of 1588.93mm (1936) to a minimum of 526.44mm (1918). Figure 40 however does not show whether this precipitation falls as snow or as rain. This is significant in terms of runoff as rain has an initial huge impact on discharge levels, whilst the majority of snowfall if stored and requires energy to be melted. Figure 41 shows a change in average air temperature levels. There is a very gradual increase in air temperature from 1901 to 2002 with minimum air temperature occurring in 1917 (19.37^{o}C) and maximum air temperature occurring in 1999 (22.13^{o}C). Despite figure 41 showing a clear increase, the change is small with data only changing by a maximum of 2.76^{o}C over the 100 year period. This difference is obviously small, however due to the regions environmental vulnerability this small change may be enough to have partially contributed to the change in river discharge displayed in the previous figures. It is interesting to also acknowledge that the basin experiences its lowest precipitation level (1918) and lowest average air temperature (1917) during almost the exact same year.

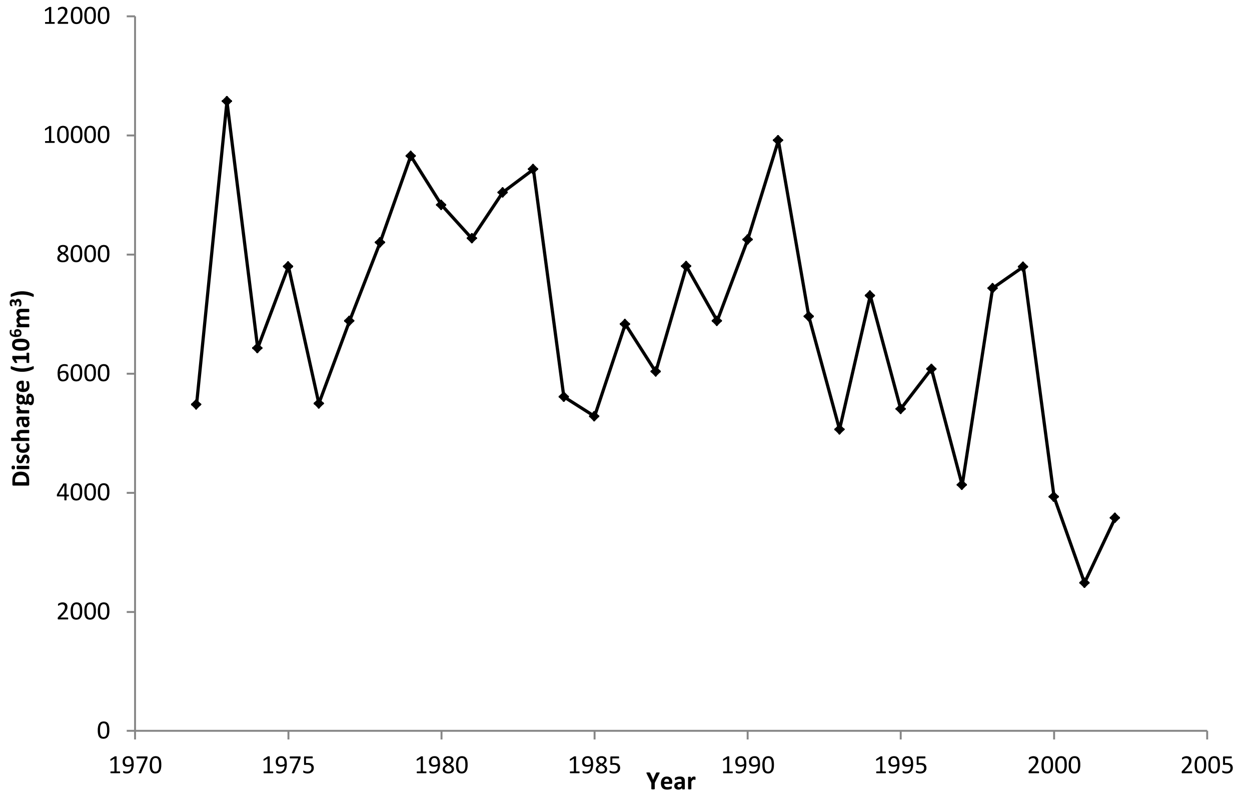


Figure 35: Discharge from the river Sutlej measured at Khab gauging station.

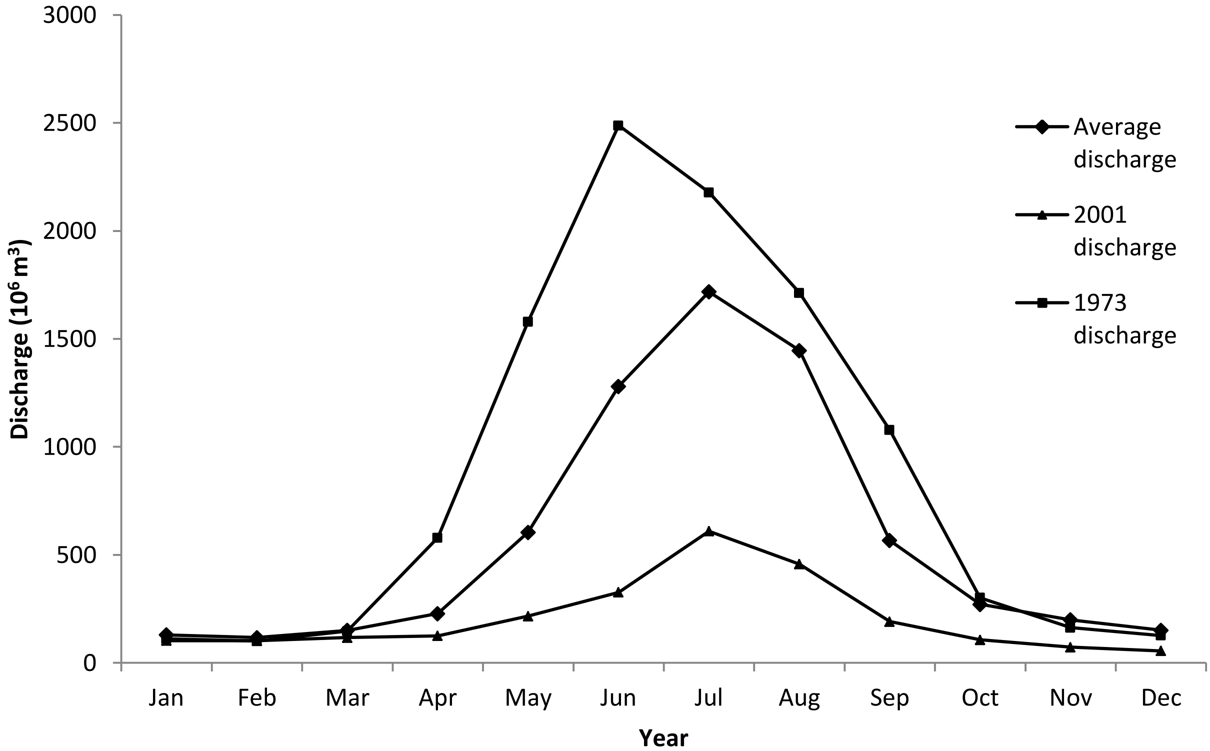


Figure 36: Change in the maximum discharge of the river Sutlej at Khab gauging station.

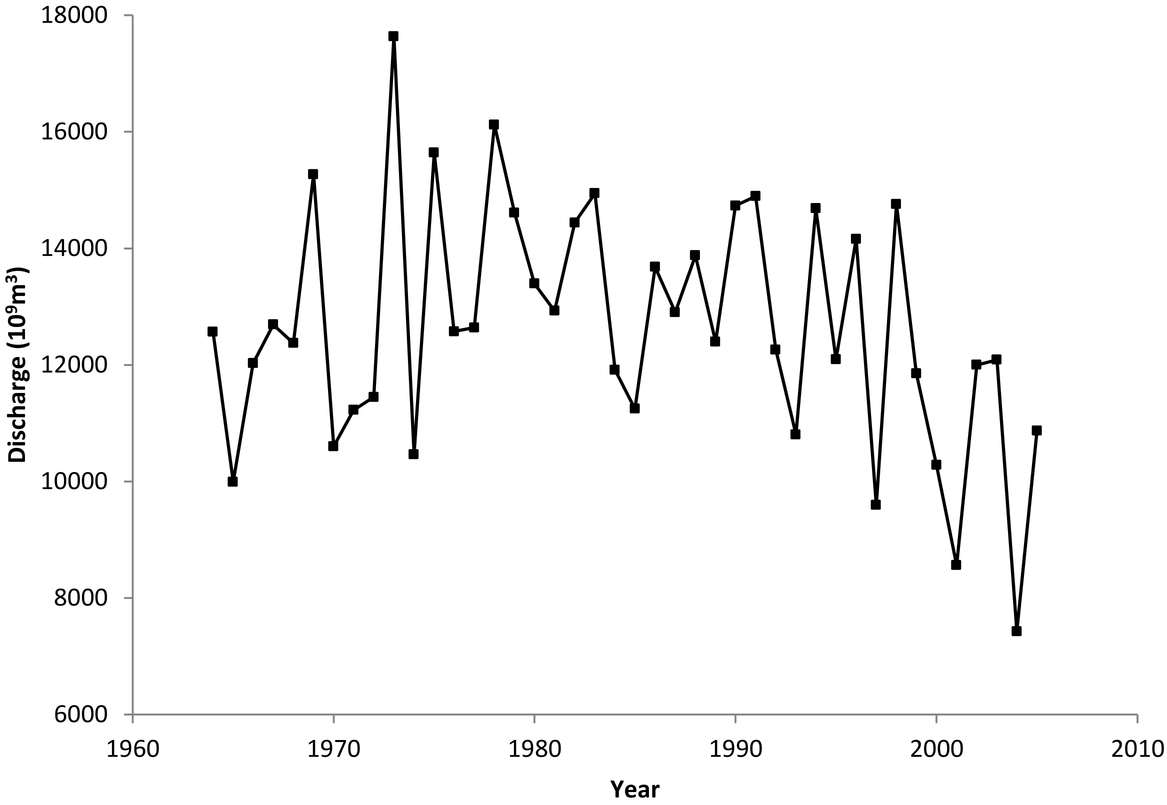


Figure 37: Discharge from the river Sutlej measured at Rampur gauging station.

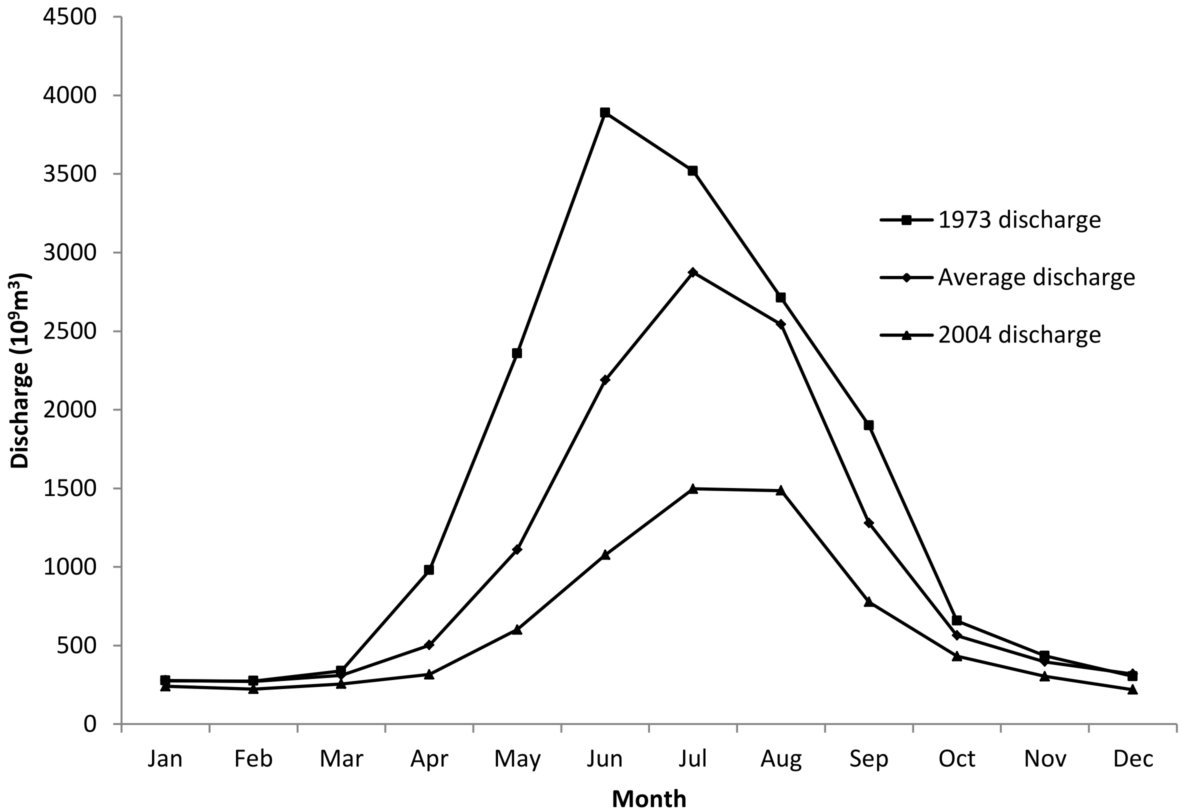


Figure 38: Change in the maximum discharge of the river Sutlej measured at Rampur gauging station.

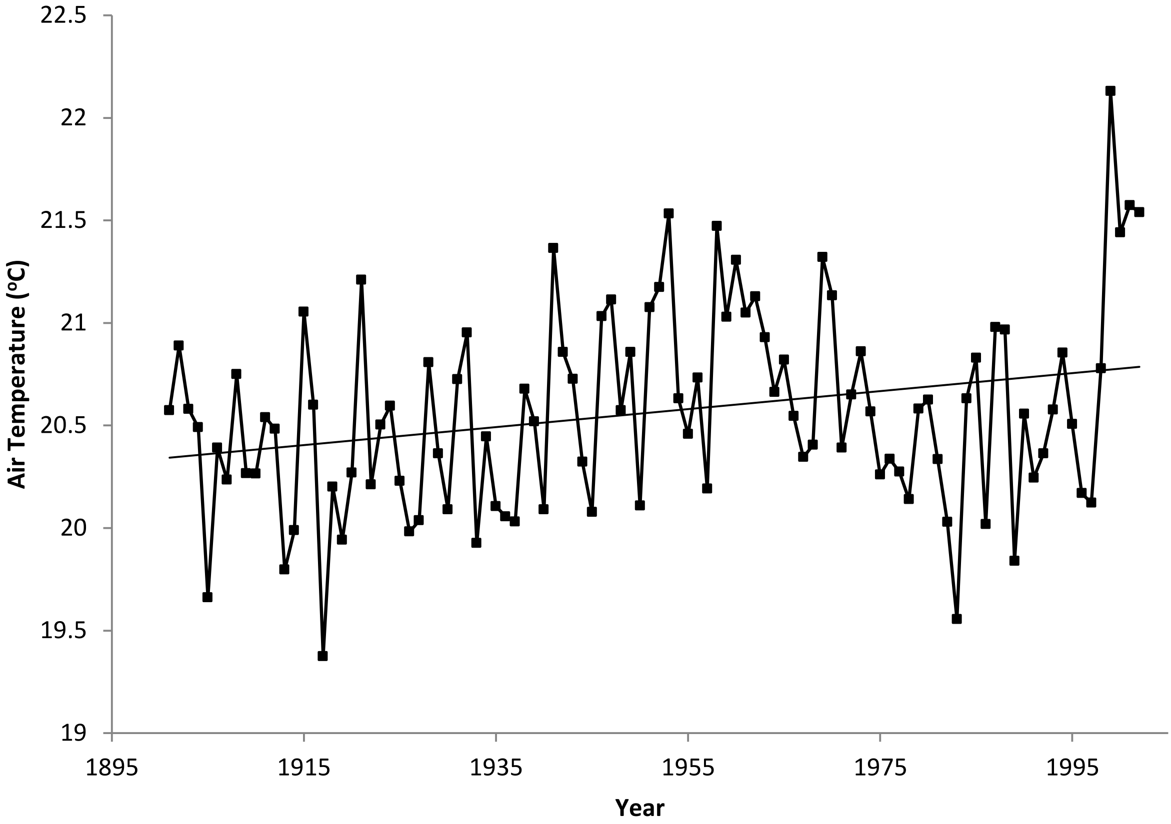


Figure 39: Annual precipitation levels within the Sutlej river basin.

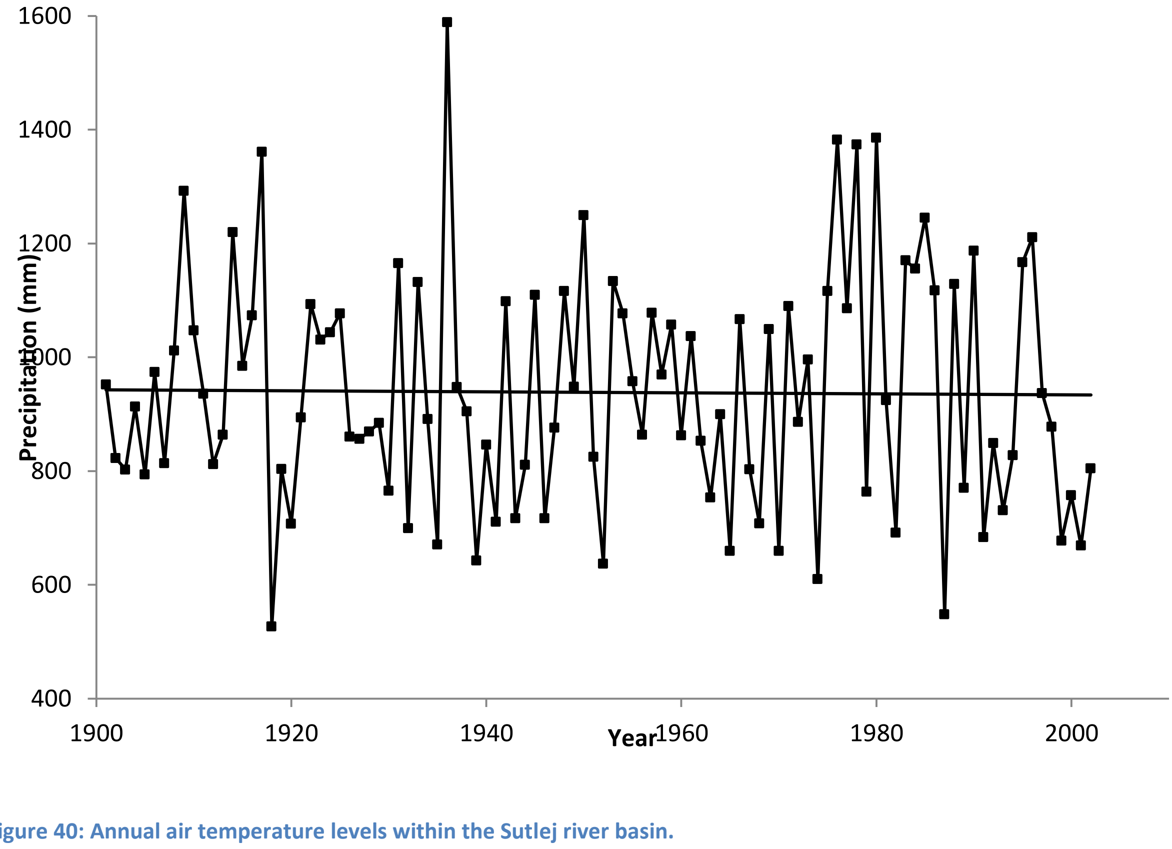


Figure 40: Annual air temperature levels within the Sutlej river basin.

4.4. Dam and reservoir development in India

The following figures show the location of hydropower development in the Himalayan states of India, the years in which developments took place, and the storage capacity of reservoirs built in the region. Understanding the level of development in India, makes it easier to interpret how hydropower development has changed in terms of the frequency of investment and the size of projects. This helps give an idea of India's strategy and how it has developed through time in light of increasing environmental and economic concern.

Figure 42 shows how many dams have been built throughout India and the years in which these developments took place. This helps explain the pattern of investment into hydropower and helps show whether future investment levels and development are going to change. Figure 42 shows that before 1900 only 67 dams were built throughout all of India. Between 1901 and 1950 however this number rises to 306 and then falls again in the 1950's to 233. After this however there is then an exponential increase in the number of dams built. In the 1970's over 1200 dams were constructed in India. This represents a huge investment in a very short space of time. The level of development is then relatively similar in the 1980's before its falls significantly in the 90's and now in the 21st century. This may be the result of a number of reasons including, a reduction in suitable locations, increased opposition, a fall in confidence surrounding hydropower, and greater concerns over negative externalities. Current downwards trends shown in figure 42 indicate that dam building will continue to reduce in India, despite growing demands for energy.

Figure 43 shows how many of these dams have been built within the 5 Indian states that border the Himalayas. Arunachel Pradesh, Himachel Pradesh, Jammu & Kashmir, Sikkim, and Uttarakhand are the five states in India that border the Himalayas, therefore the rivers dam construction that exists within them are guaranteed to be along Himalayan sourced rivers. Figure 43 shows that the majority of development occurs within Uttarakhand, Himachel Pradesh, and Jammu & Kashmir, the northern most states of India. Development in the other two more eastern states however is minimal. In comparison to other states throughout India, dam construction in these five states is relatively small with the greatest level of dams being present within more central and Western states of India, in states such as Madhya Pradesh and Maharashtra.

Figure 44 shows the size of the dams that exist within these five bordering states. Gross storage relates directly to the size of a reservoir and describes the scale in which a dam is able to store water. Figure 44 shows that the majority of the dams built within these five Indian states have a storage capacity of between 10,000 and 100,000 10^3m^3. Dams with storage capacities of more than 500,000 10^3m^3 however are sparse. This is possibly because dam size correlates directly with increased cost and environmental impact. Smaller dams are however more numerous with dams with a storage capacity of up to 100,000 10^3m^3 making up a large percentage of the dams present within the region. It is expected however that there are a greater percentage of smaller dams as larger dams require a more appropriate location, greater investment, and also generate greater opposition and externalities.

Figure 45 is again related to the storage capacities of dams in the five Indian states already mentioned. This figure however helps explain how the storage capacity of projects has changed through time. From figure 45 it is instantly obvious that the size of dam projects has reduced through time. The average year in which dams with a storage capacity of over 500,000 10^3m^3 were built is 1981. The average year in which dams with a capacity of between 1,000 and 10,000 10^3m^3 were built however is 1999. This is a significant difference and shows that dam building has become more small scale in recent years, adapting to changing attitudes toward the industry. Mega dams are now recognised as being more damaging both environmentally and socially. This has meant that a greater number of small projects have had to be built to match the generating capacity of a fewer number of larger projects. It is also now more difficult for mega dams to be built in areas surrounding the Himalayas as they are now so densely developed leaving only a few locations for future potential investment. Figure 45 shows that as time goes on dams have become smaller. As a result, it is likely that in the future even fewer large dams will be built and an increasing number of smaller scale developments are to be planned.

Figure 41: The number of dams built in India and the years in which these developments were finished.

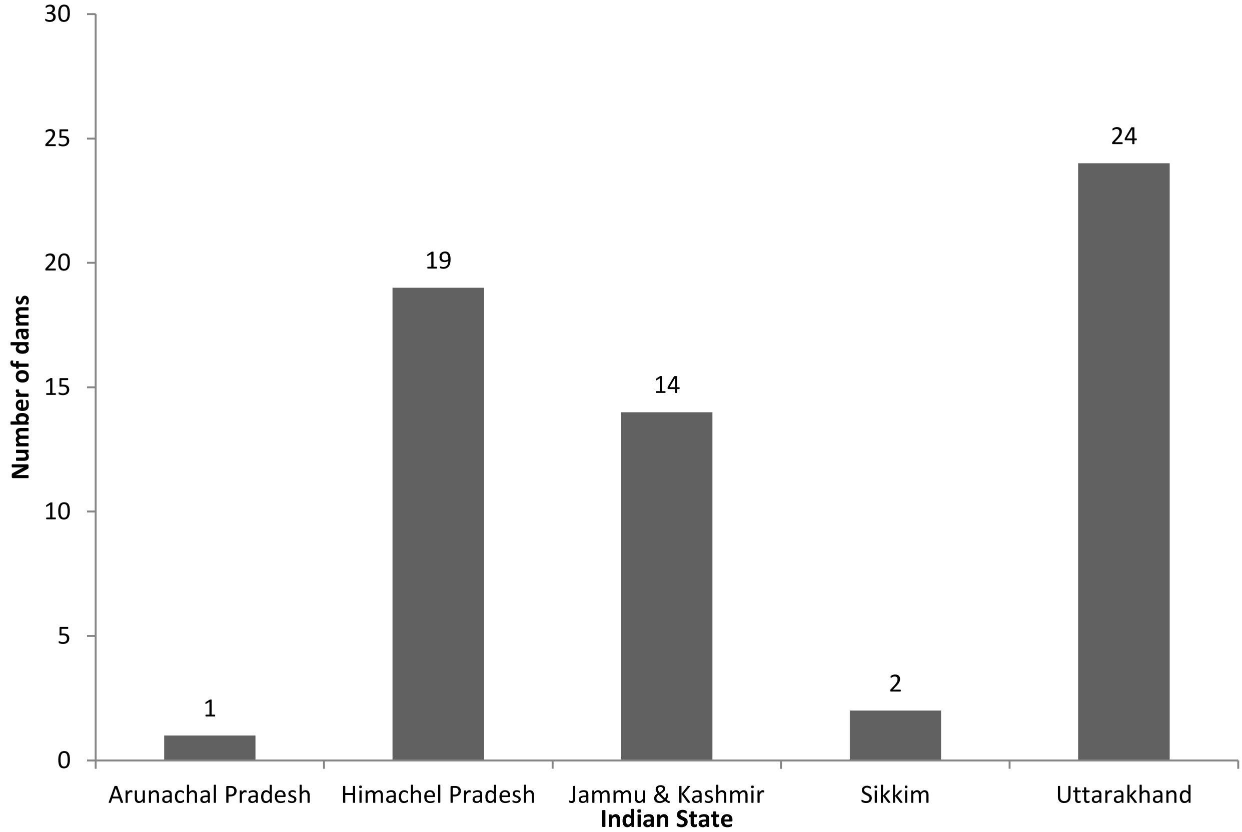


Figure 42: The number of dams built in the five states of India that border the Himalayas.

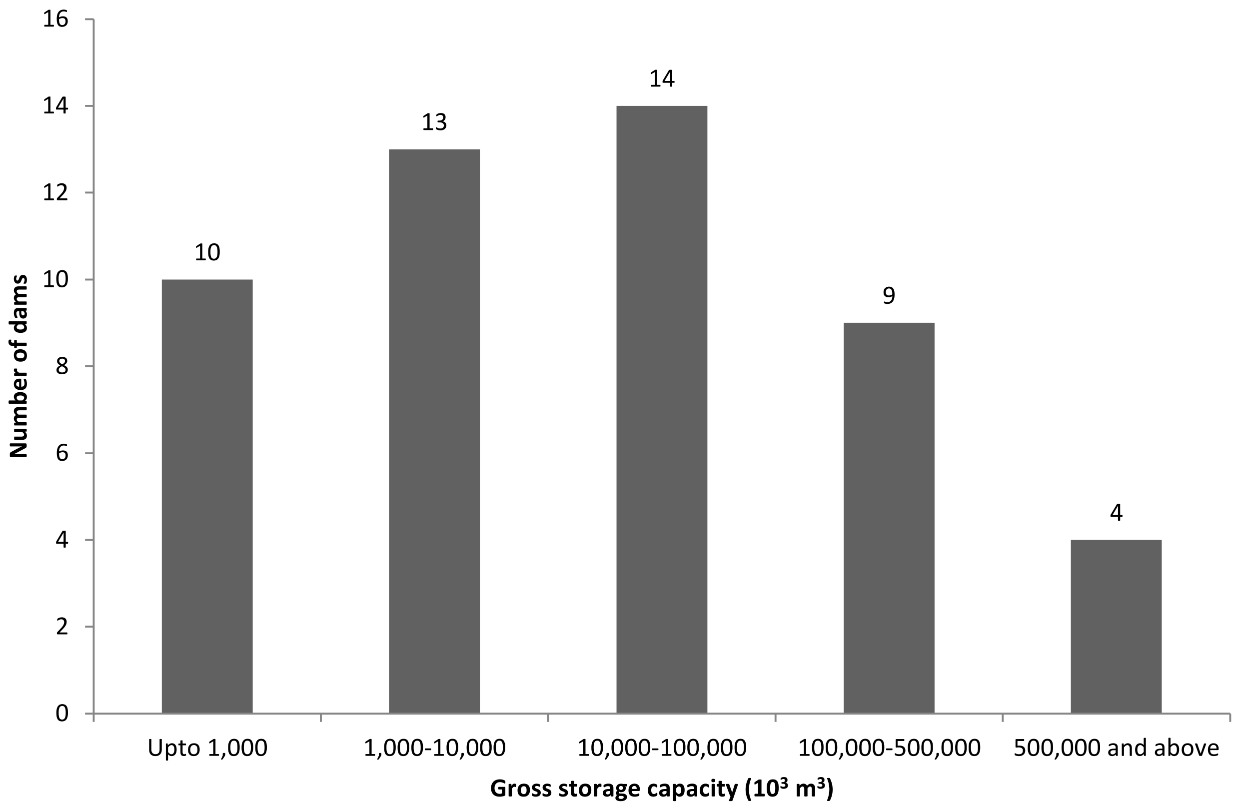


Figure 43: The storage capacities of the dams built within the five states of India bordering the Himalayas.

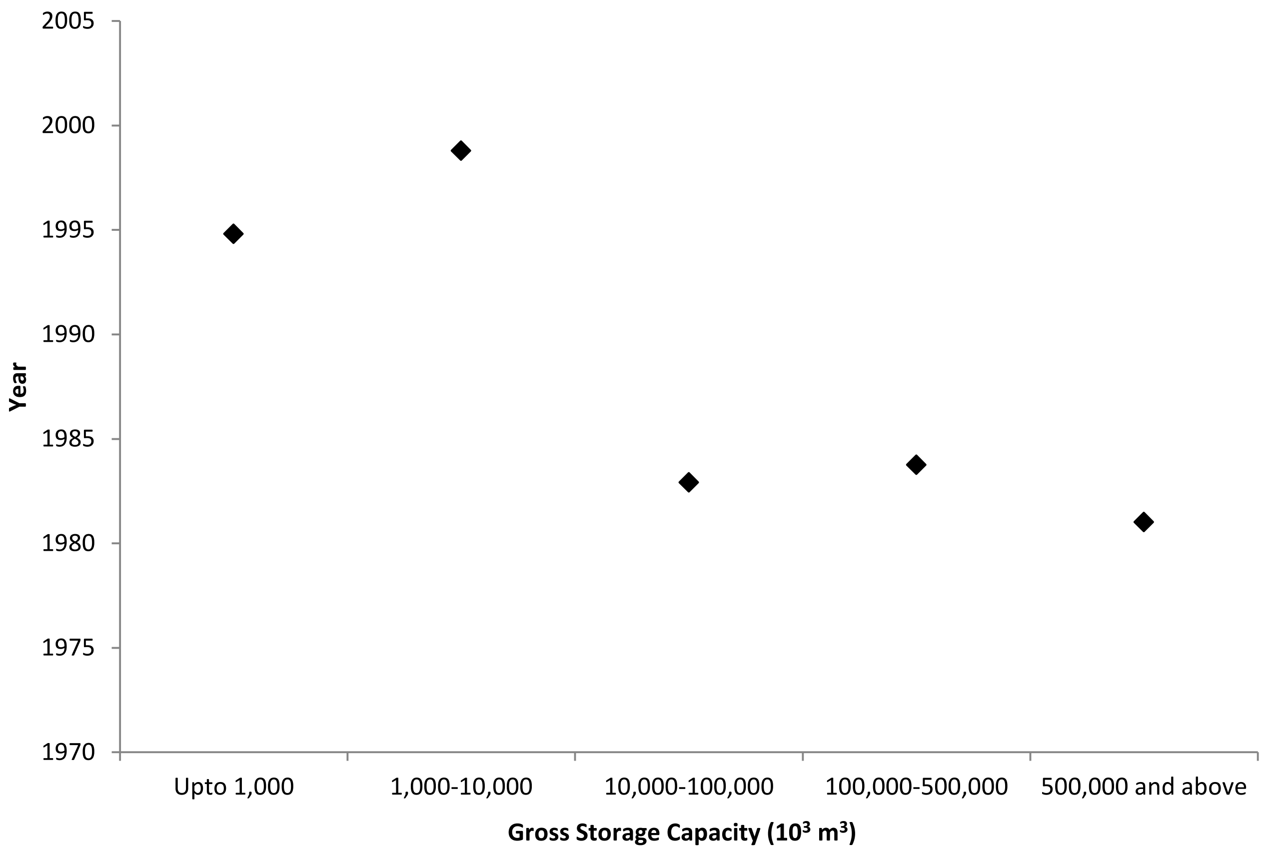


Figure 44: The size of the dams built in the five states of India and the average year in which they were built.

4.5. Tarbela Dam sedimentation

This section of the thesis mainly focuses on the sedimentation of Tarbela Reservoir. Sedimentation represents one of the greatest threats to the financial feasibility and sustainability of dams throughout the world. Figures 51 and 52 show the level of river discharge and sediment inflow at Tarbela Reservoir respectively, whilst figure 53 shows both graphs plotted against one another so their relationship can be more easily interpreted. Understanding how sedimentation is affected by discharge could be beneficial in terms of mitigating runoff in an attempt to control sedimentation rates. Figures 54 to 58 show cross sections of Tarbela reservoir at five different locations, so that rates of sedimentation within the infrastructure can be more broadly understood. Understanding where the greatest threats lie will also lead to the more successful implementation of mitigation strategies. Figure 59 also shows the change in sediment bed load through time across the entire reservoir cross section.

Figure 46 shows that river discharge at Tarbela dam has remained relatively constant from 1962 to 2009 despite large fluctuations in the data series. The figure however shows that these fluctuation increase in frequency after roughly 1984. This poses potential risk in relation to droughts and extreme floods, making water management and storage more crucial at Tarbela. This will also cause efficiency problems in relation to hydropower as river discharge directly relates to generation. The greatest discharge level occurred in 1973 at 102,018 10^6m^3 whilst the smallest occurred in 1982 at 63,229 10^6m^3. This is a huge difference and will particularly cause problems in relation to water and energy as demand for these resources is far more consistent.

Figure 47 also shows that sediment inflow has remained very consistent from 1980 to 2012 despite large fluctuations in the annual data. This supports current theory that suggests sediment flow is directly correlated with river discharge. Fluctuations in figure 47 however do not increase in frequency through time like in the previous figure. The scale of the fluctuation is however far greater in terms of percentage change. From just 2009 to 2010 the change in sediment flow is exponential. In 2009 sediment inflow was recorded at $47Mm^3$, whilst in the following year sediment inflow was recorded at $243Mm^3$. This represents a percentage increase of 81% in just one year. This makes accurate future predictions very difficult to achieve as year to year variability is so high.

Figure 48 also supports the theory that discharge and sediment inflow are directly related as the graph demonstrates strong correlation. As discharge increases, so does the level of sediment inflow. After 2001 however this relationship becomes more unpredictable as the two data sets begin to correlate more weakly. This may be the result of an increase in the exploitation of the river runoff upstream of Tarbela, or the implementation of mitigation strategies altering the level of sediment being present in the rivers flow for example. A reduction in the correlation of these two sets of data however may potentially make it more difficult to make predictions over sedimentation. As a result, inaccurate estimations over maintenance costs and reductions in storage capacity may occur.

Figure 49 shows how the level of sediment in Tarbela reservoir has changed from its original construction in 1976, to 1979, and then to 2008 at a distance of 1km upstream of the dam wall. Between the dam's original construction data and 1979, the sediment bed load actually falls by a few metres. This is potentially an anomaly in the data; however it could also be the result of the increase in weight of water now present on top of the sediment resulting in increased compaction. Between 1979 and 2008 however there is a large increase in the bed load in comparison. The increase is also very consistent across the entire cross section with the new level being approximately 370ma.s.l. This represents an increase in height of roughly 22m in 29 years across the whole width of the reservoir at this distance.

Figure 50 shows the cross section of the reservoir at 28.4km upstream of Tarbela dam. Here there is a far greater gain in sediment bed load with sedimentation also occurring greatly between the reservoirs original level and 1979. Sedimentation at this distance is the greatest witnessed in this research. The greatest change in sediment level at this location from its original to 2008 was 59m. The reason for this large increase in sediment level is down to the location from which this data has been collected. This data was collected from an area of the reservoir bed known as the pivot point where the greatest level of sedimentation is often realised. This is the position where the greatest level of deposition takes place. This is because at this point the river discharge loses its capacity to carry sediment thanks to a reduction in velocity. Figure 50 also shows that the rate of sedimentation is far faster just after construction was finished at Tarbela, than it was in more recent years. This is a surprising finding, particularly in light of predicted increases in erosion and glacial melt.

The remaining three figures that show the reservoirs cross sections at 37.6km, 43.9km, and 52.6km are all very similar in relation to changing sedimentation levels. All figures show a strong growth in sediment level, however it is not as pronounced and as extensive as in figure 49. It is clear from these figures that the shape of the reservoir is also changing as sedimentation rates differ along the width of each cross section, whilst the previous two figures show a far more consistent pattern. The greatest change in sediment level for each of the locations is approximately 45m which is a significant difference. It can be realised however that changes in the sediment level at these three distances is less significant as they are located further from the dam wall. This means they offer less of a threat in terms of damage to infrastructure and storage capacity.

Figure 54 shows how sedimentation has affected all of Tarbela reservoir from its original construction in 1976 to 2007. The figure effectively shows a side profile of the reservoir and demonstrates how the river has changed through time as a result of sedimentation. Figure 46 clearly indicates that the pivot point of the reservoir exists at approximately 15km from the dam wall. This is also the location of the greatest accumulation of sediment along the whole reservoir. This figure also shows that after the pivot point, sedimentation rates become less with distance from the dam wall. Figure 54 shows that the accumulation of sediment within the first 15km of the reservoir is extremely small. This will be the result of the majority of sediment already being deposited before it has reached this area of the reservoir. The impacts that sediment can have in this location are however far greater than anywhere else along the reservoir. Sedimentation has only caused the bed level to rise by 19m alongside the dam wall which is particularly small in relation to a 60m increase at approximately 15m from the dam wall. Figure 54 also shows that the level of fluctuation in sediment level increases with distance from the dam as the dams shape becomes more irregular.

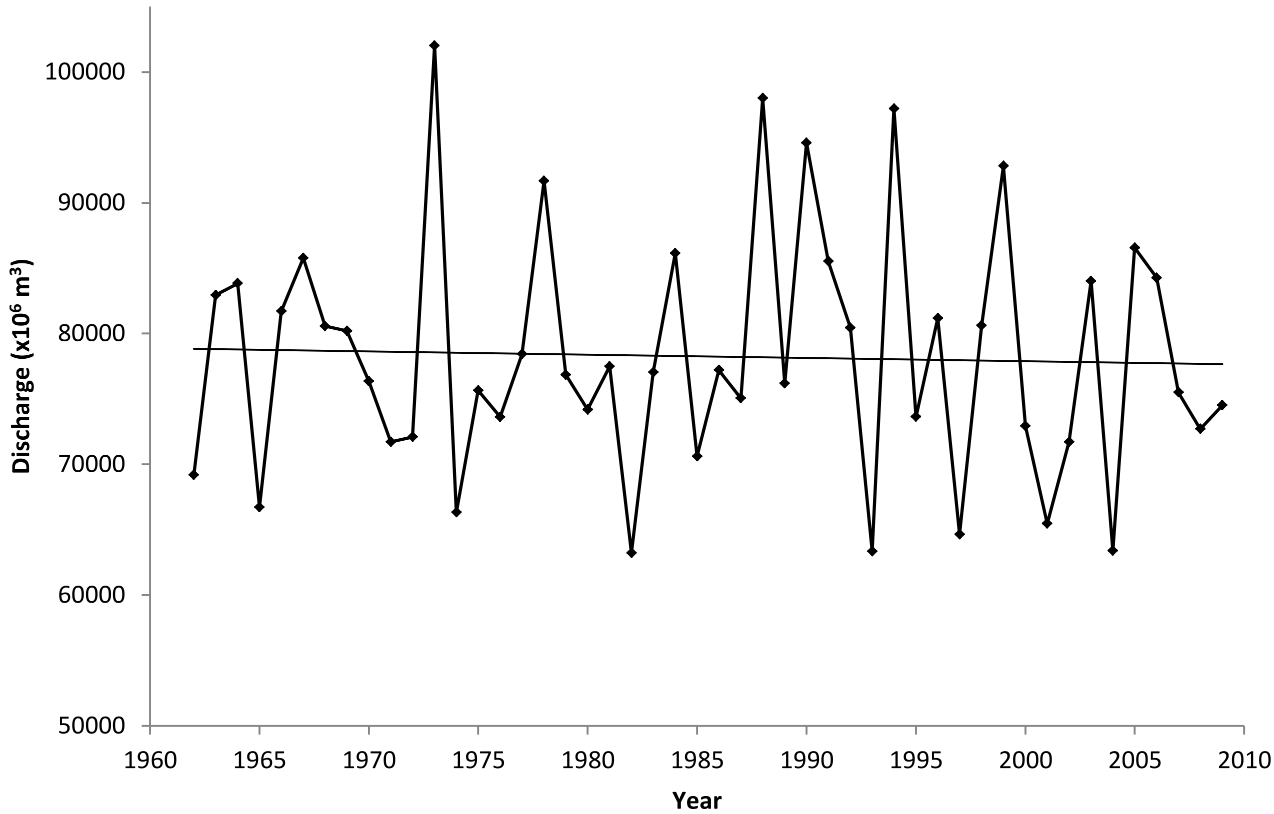


Figure 45: Discharge from the river Indus measured at Tarbela dam.

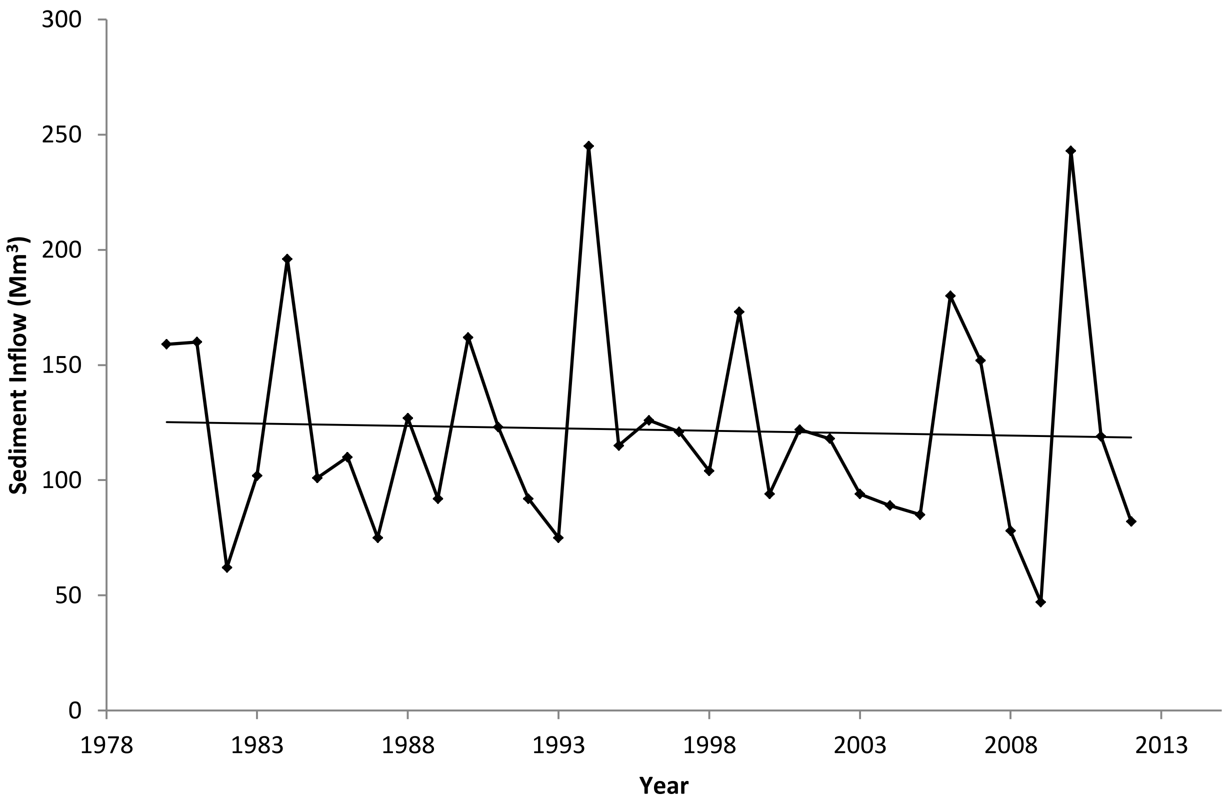


Figure 46: Sediment inflow at Tarbela reservoir along the River Indus.

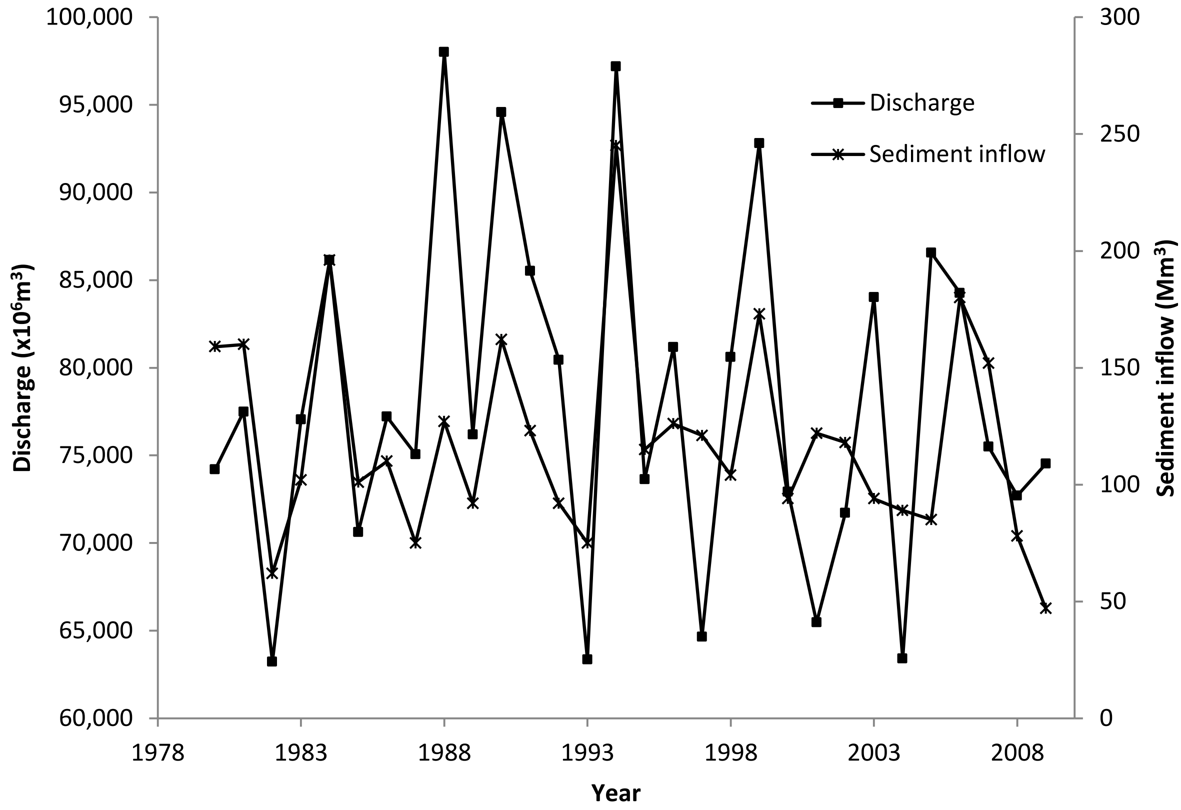


Figure 47: Relationship between river discharge and the inflow of sediment at Tarbela reservoir.

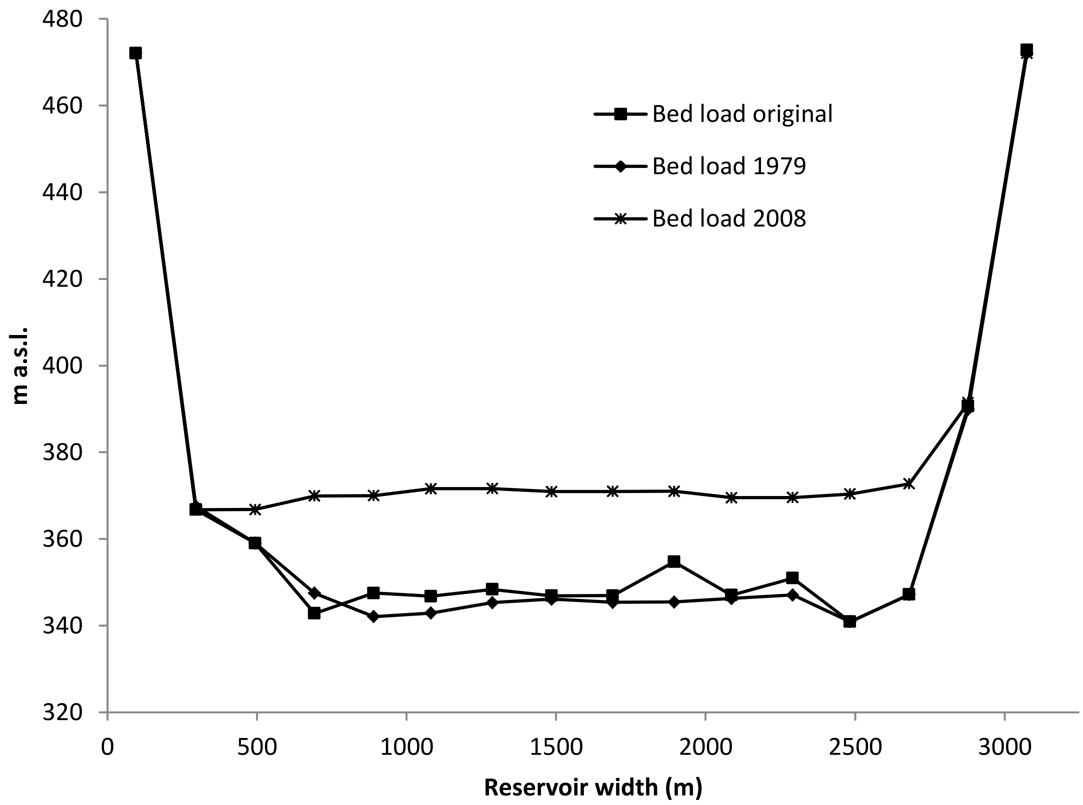


Figure 48: Cross section of Tarbela Reservoir showing the change in sediment bed load level at 1.0km from the dam.

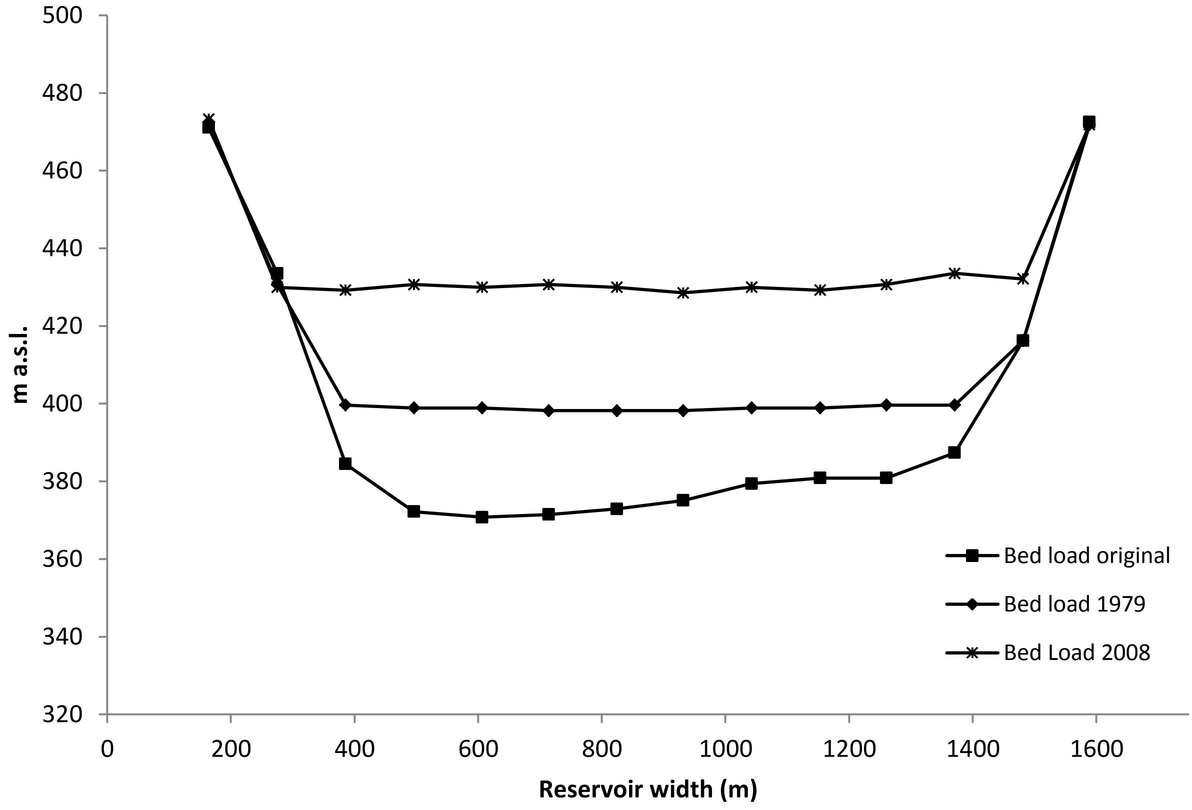


Figure 49: Cross section of Tarbela Reservoir showing the change in sediment bed load level at 28.4 km from the dam.

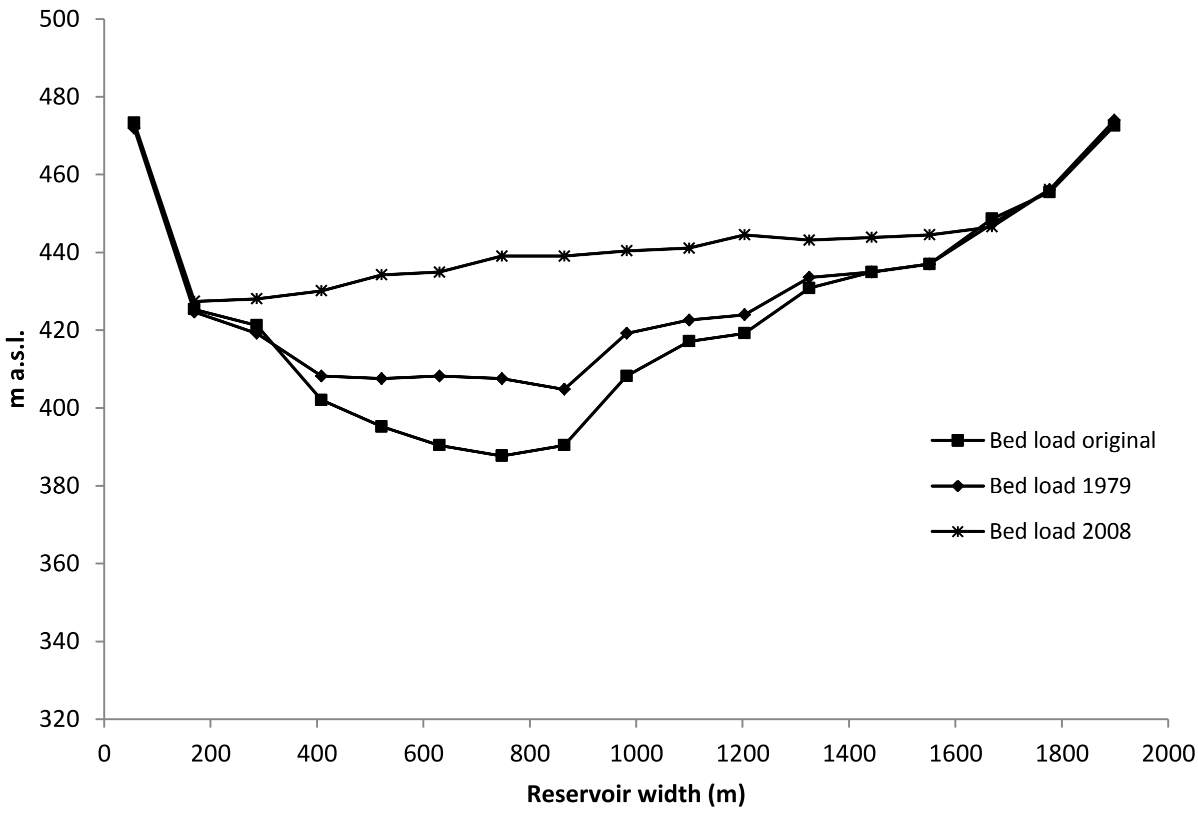


Figure 50: Cross section of Tarbela Reservoir showing the change in sediment bed load at 37.6km from the dam.

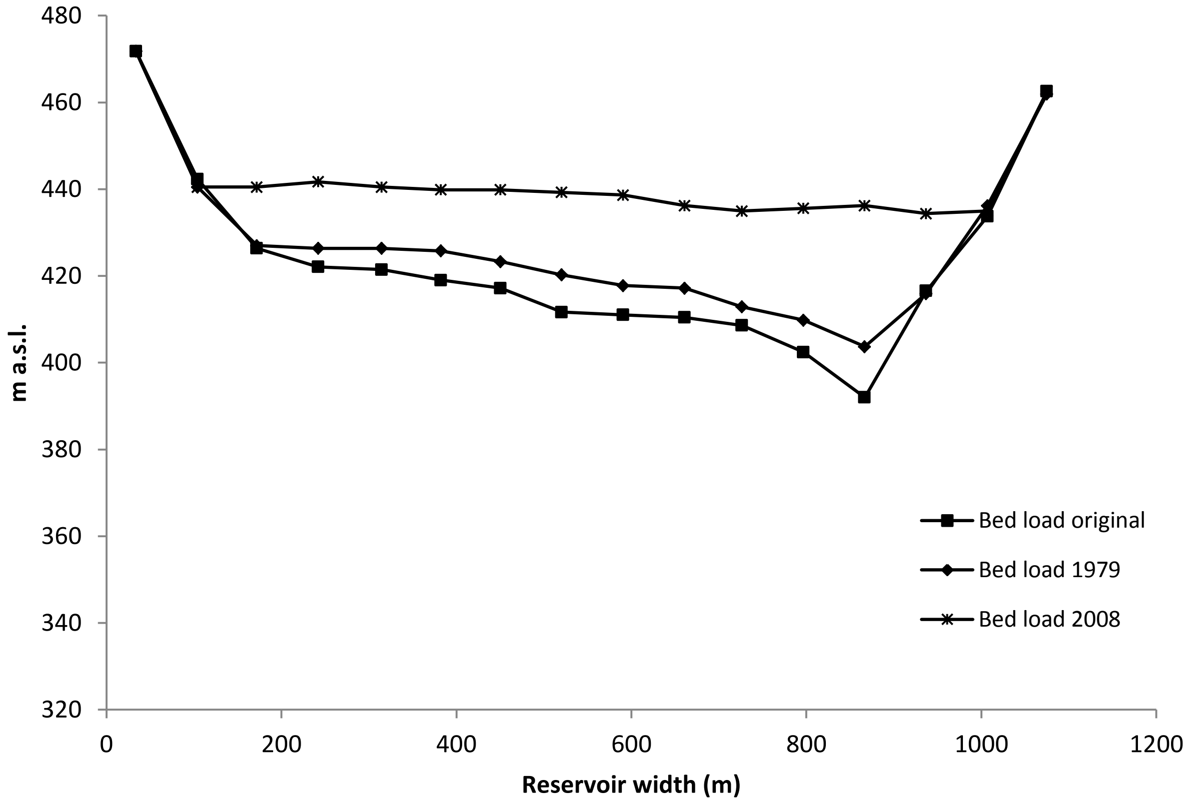


Figure 51: Cross section of Tarbela Reservoir showing the change in sediment bed load at 43.9km from the dam.

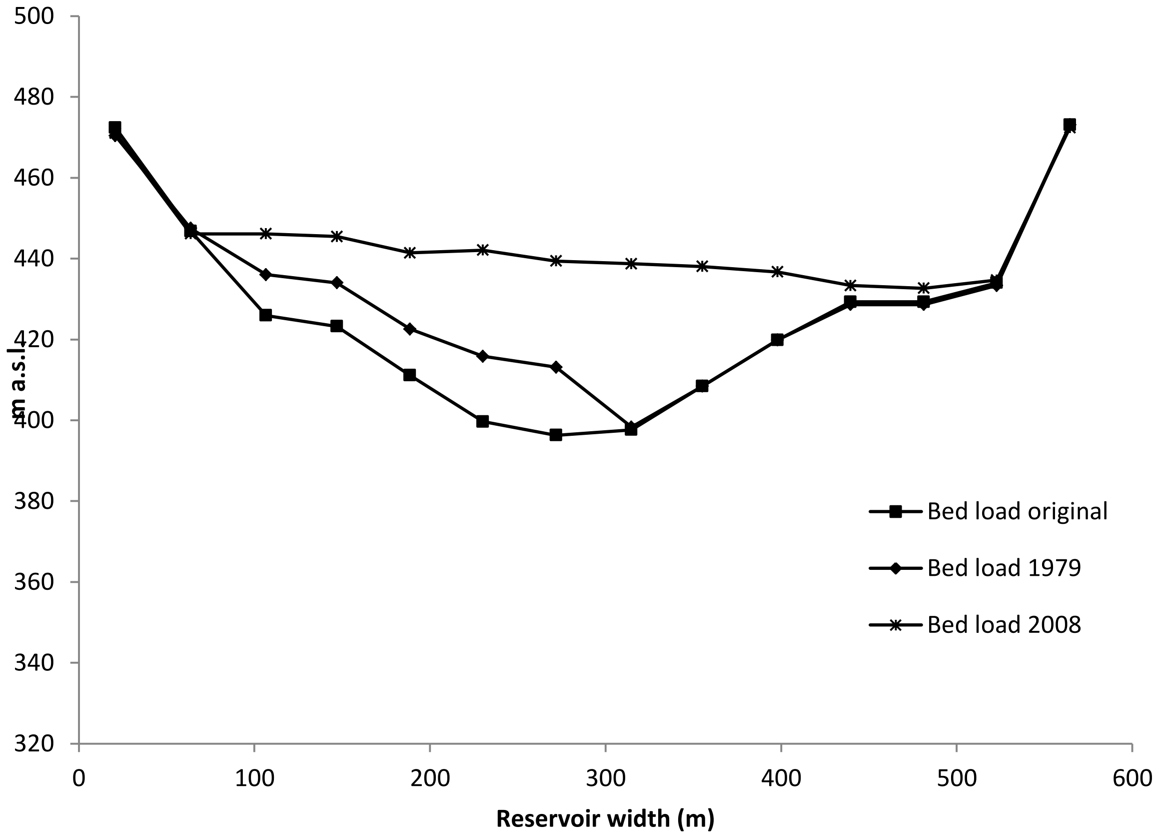


Figure 52: Cross section of Tarbela Reservoir showing the change in sediment bed load at 52.6km from the dam.

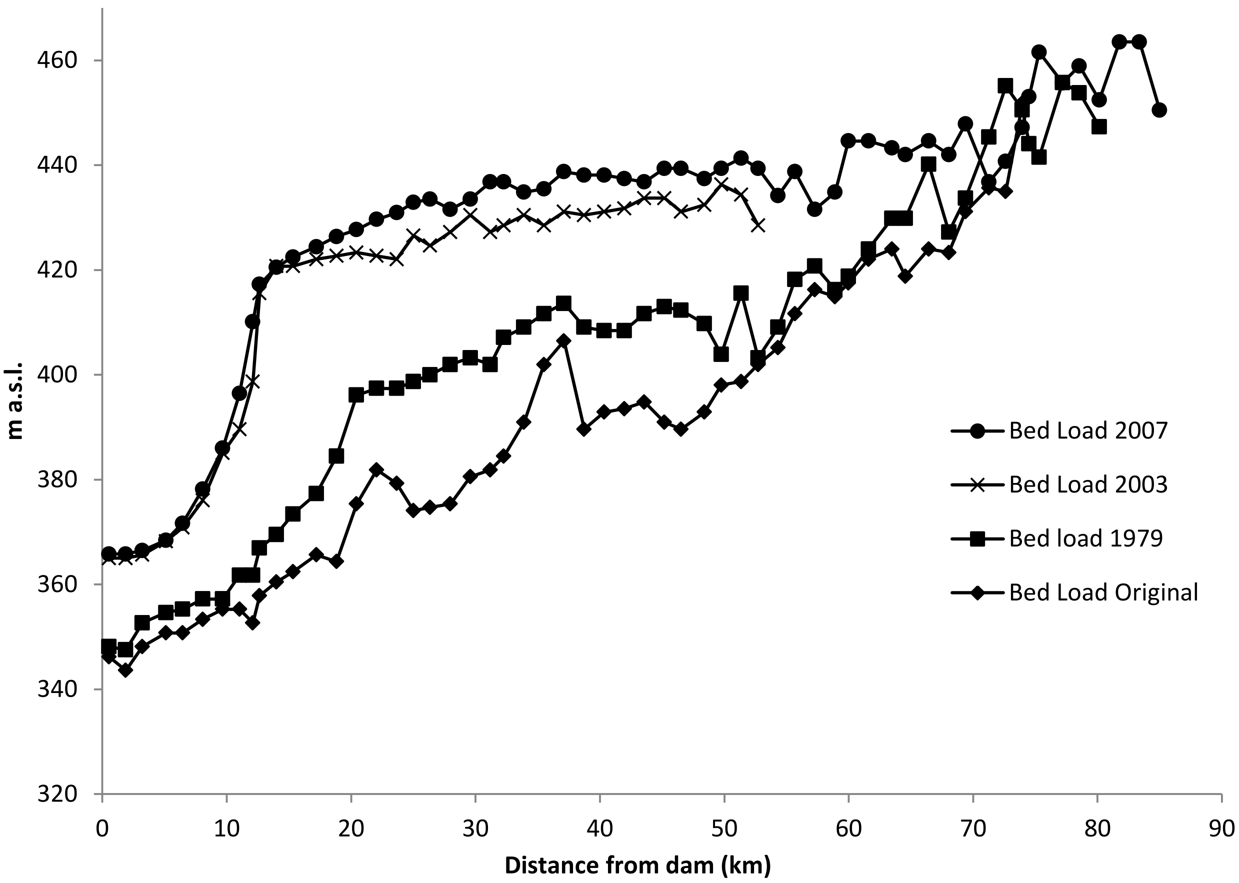


Figure 53: Cross section of Tarbela Reservoir showing the change in sediment bed load through time.

4.6. Tarbela Dam sedimentation estimations

The following graphs are re-engineered versions of the previous six figures. Figures 55 to 59 show estimations of future sediment bed load level at five different locations along Tarbela Reservoir. These figures are displayed as cross sections of the reservoir and have been generated using existing data. The figures are also based on the understanding that future sedimentation rates will remain stationary as shown by figure 47. Figure 60 also makes estimations from existing data to generate a graph that shows how the sediment level in Tarbela reservoir may change through time. Like figure 54 this data is plotted in such a way that shows the change and potential future change in the entire side profile of the reservoirs bed level. Making calculated and accurate decisions on reservoir sedimentation is extremely challenging, particularly when considering the fluctuations shown in annual sedimentation data and risks relating to climate change. Making predictions however could potentially aid more successful mitigating strategies to be employed and may also encourage greater research into an increasingly important phenomenon.

Figure 55 shows the future sediment bed level estimations within Tarbela reservoir at 1.0km's distance from the dam wall. Here there is predicted to be only a small increase in sediment build up. This is simply because the build-up of sediment that has already been realised since construction has only been minor, particularly in comparison to other areas along the reservoir. The highest level of sediment predicted at this distance in 2030 is 393m a.s.l. which is 47m higher than it was after its initial construction in 1976. Despite being a small increase in comparison to the other locations, this is a significant increase at such a local distance from the dam wall. At this distance the sediment greatly threatens to damage the dams operating infrastructure, including turbines and intake pipes. Sediment at this location also poses the most consistent threat to storage capacity as even during periods of low flow it will be submerged beneath the runoff.

Figure 56 shows estimations on future sediment bed load at a distance of 28.4km from the dam wall. Here the greatest increase is predicted due to the highest rate of sedimentation already present at this location. By 2030 it is predicted that if unmitigated sediment levels will have completely overreached the boundaries of the reservoir, resulting in a 100% loss in storage capacity at this location. Current trends suggest that by 2030 the highest sediment level at this location would be 28m above that of the maximum potential water level. It is obviously impossible for this to happen however this helps explain how quickly Tarbela reservoir is collecting sediment. The highest level of sediment estimated in 2030 is 503m a.s.l. This sediment level is 133m higher than its original sediment level in 1976, representing a huge change in storage capacity. It is clear that within this location particularly, mitigation strategies are essential to reduce the rate at which sedimentation is occurring. Figure 56 suggests that ignorance toward these findings will lead to the development being rendered unsustainable far before 2030.

Figure 57 also shows estimations of sediment bed level at 37.6km from the dam wall given sedimentation rates remain stationary. Here there is also predicted to be a relatively large scale increase in sediment bed load up to 2030. Like in the previous figure the predicted bed load level for 2030 overreaches the boundaries of the reservoir. The highest level of sediment estimated at this location for 2030 is 494m a.s.l. This level is 107m higher than it was during its initial construction, again representing a huge loss in storage. This figure however shows that the majority of sediment level gain is located within the centre of the reservoir, however in real terms this sediment would spread out, reducing the height at which sediment was present. It is unlikely that the sediment would spread evenly however as the natural shape of the river bed indicates that sediment will be deposited irregularly.

The remaining two figures show predictions at distances of 43.9km and 52.6km from Tarbela dam. Both are very similar in relation to the change in sediment level predicted through time. Here the future sediment bed level is less of an immediate issue compared with further downstream. Sediment at these locations could potentially however prevent water from flowing comfortably further into the dam as it blocks the rivers natural course. For both figures the predicted change in sediment bed level from the dam's original construction to its 2030 prediction is less than a 100m gain. From studying the shape of the bed load shown in both figures 58 and 59 it again suggests that the reservoir is slightly curved which means deposition does not occur consistently along the width of the reservoir. This is also the result of differing depths in the reservoir which will encourage a difference in the carrying capacity of the rivers flow. The highest predicted levels in figures 58 and 59 also outreach the boundaries of the reservoir which is hugely damaging in terms of storage capacity.

Figure 60 shows estimations of future sediment bed load at Tarbela reservoir using a graph designed to give the impression of a reservoir side profile. The results here should mirror those of the previous 5 figures as data is taken and estimated from the same locations. The least change in sediment bed load occurs at the front of the reservoir alongside the dam wall. There has only been a predicted change here of approximately 35m over roughly 60 years. Further upstream however the predicted change in bed load becomes far more pronounced. This is particular y the case after a distance of 15m from the dam wall where bed load change is predicted to be its most significant. This estimated gain in bed level is relatively consistent up until roughly 50m from the dam wall where it then begins to reduce. This is because the carrying capacity of the river reduces as it travels closer to the dam meaning deposition occurs more frequently. It can also be seen from figure 60 that the pivot pint has begun to encroach on the dam very slowly as the sediment level has increased. This is potentially concerning as the closer to the dam this sediment grows, the more vulnerable the infrastructure is to damage.

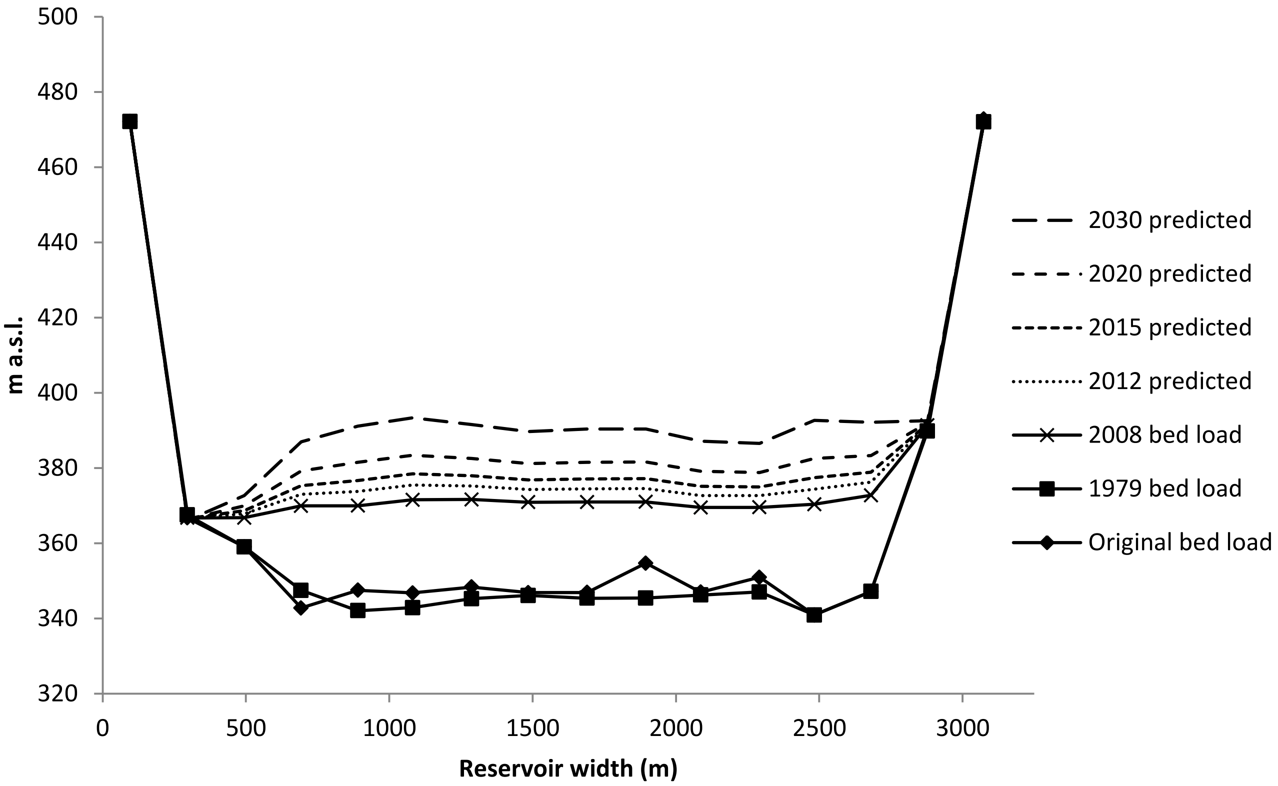


Figure 54: Cross section of Tarbela Reservoir showing future predictions of sediment bed load levels given sedimentation rates remain constant at 1.0km from the dam.

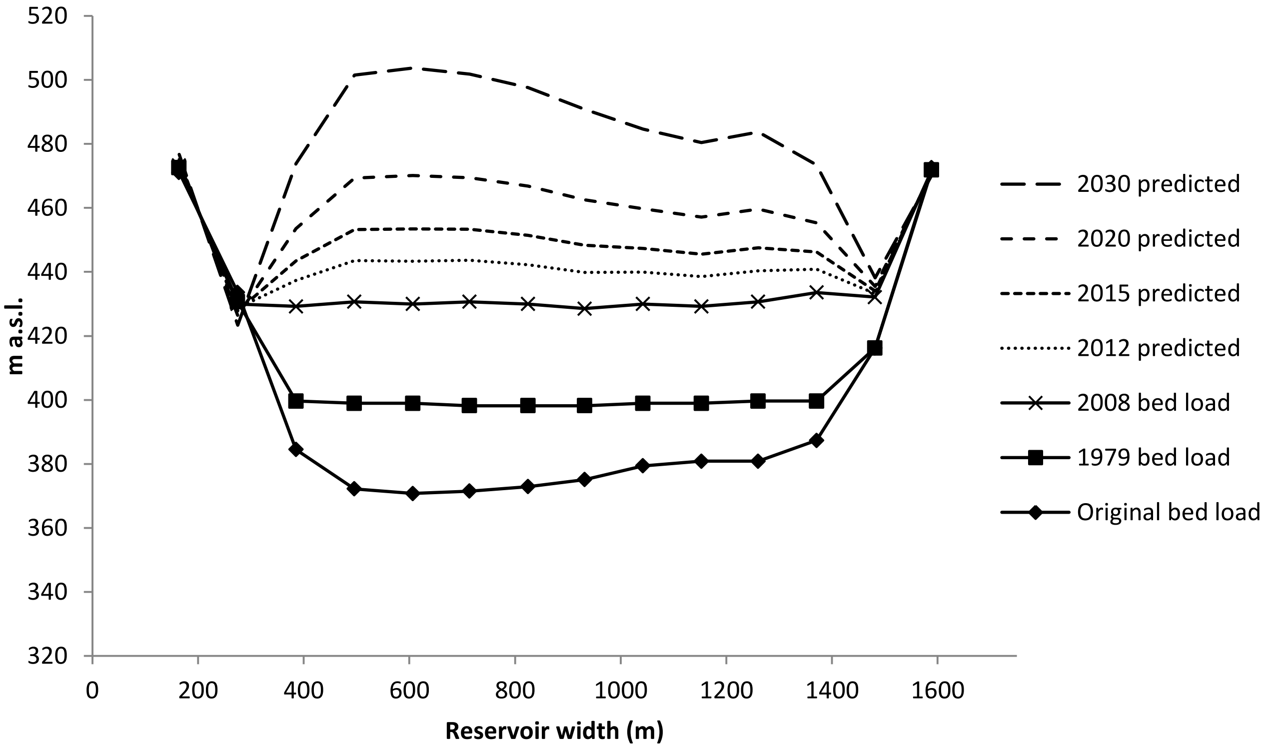


Figure 55: Cross section of Tarbela Reservoir showing future predictions of sediment bed load levels given sedimentation rates remain constant at 28.4km from the dam.

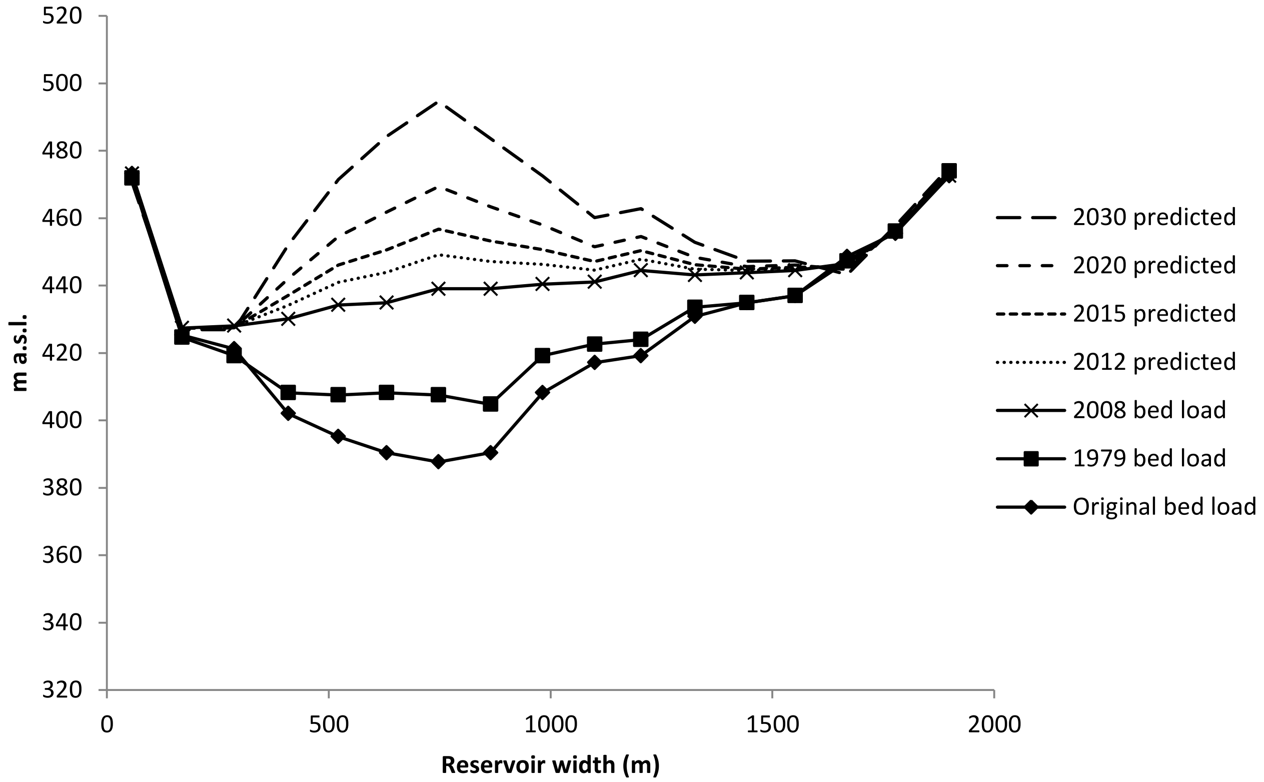


Figure 56: Cross section of Tarbela Reservoir showing future predictions of sediment bed load levels given sedimentation rates remain constant at 37.6km from the dam.

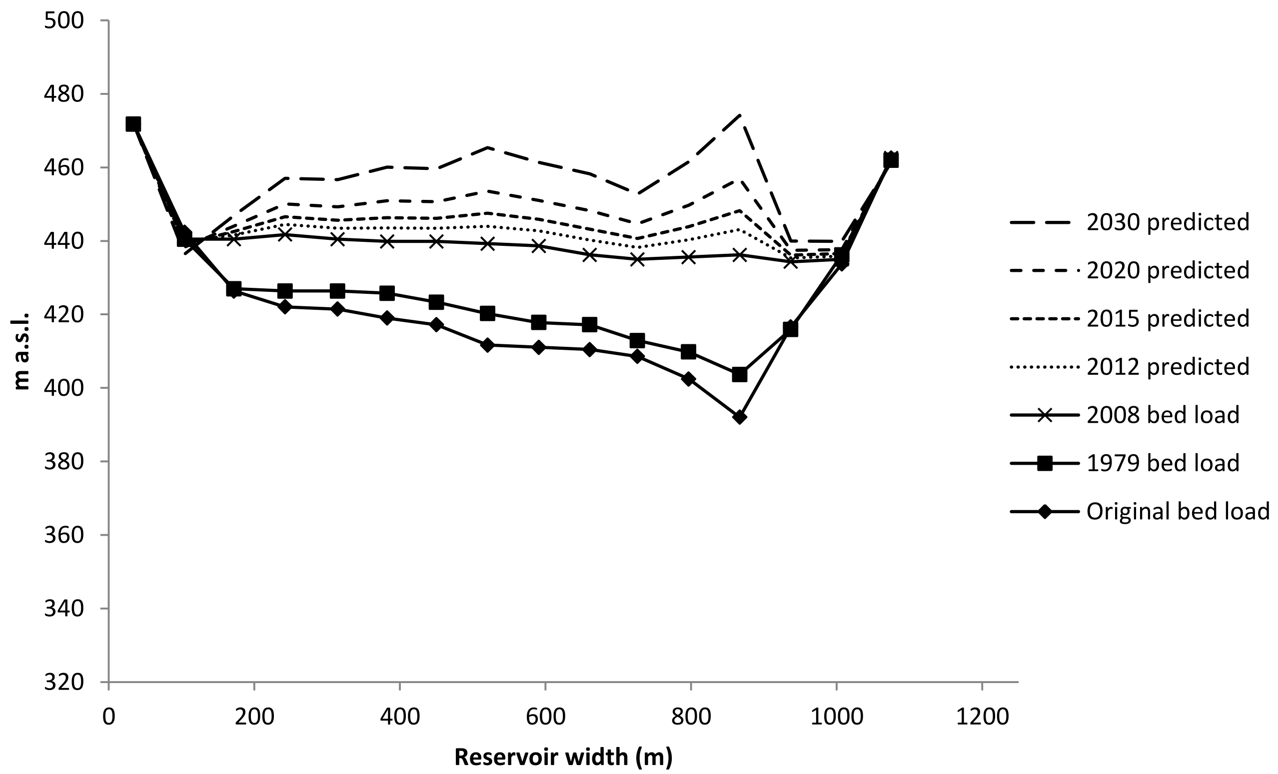


Figure 57: Cross section of Tarbela Reservoir showing future predictions of sediment bed load levels given sedimentation rates remain constant at 43.9km from the dam.

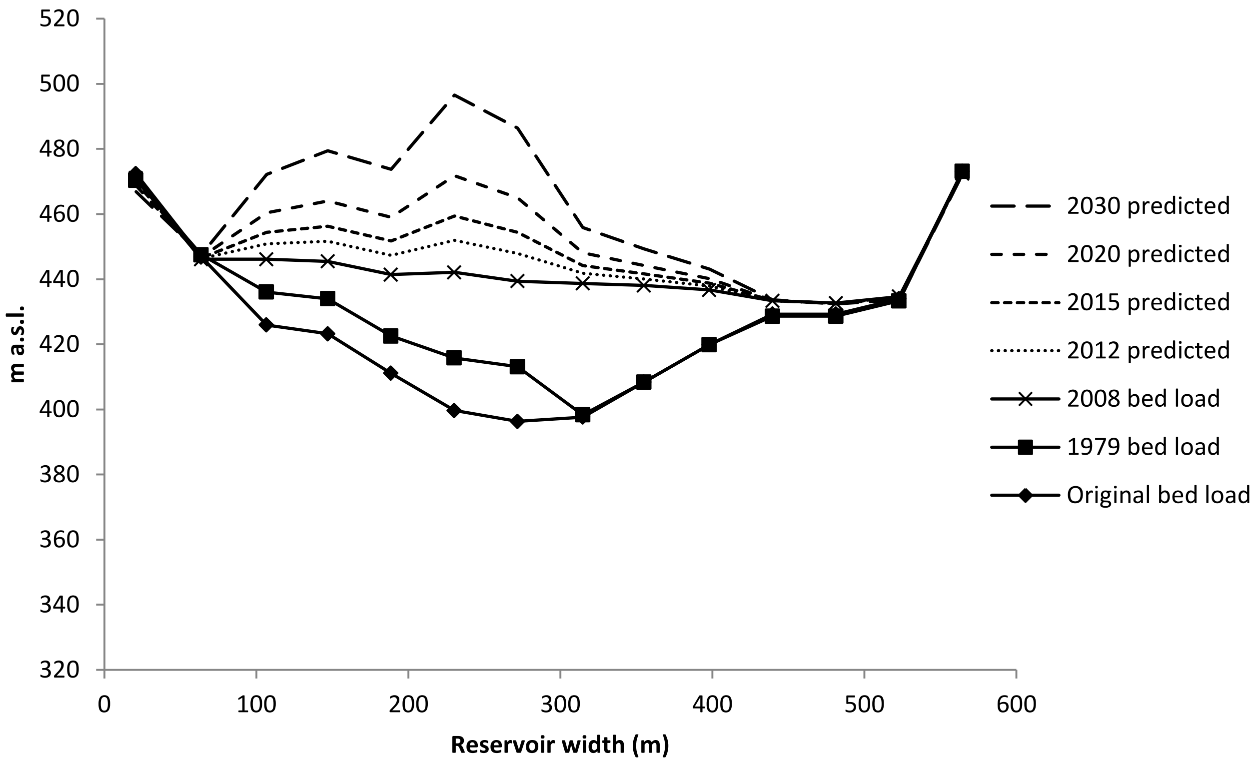


Figure 58: Cross section of Tarbela Reservoir showing future predictions of sediment bed load levels given sedimentation rates remain constant at 52.6km from the dam.

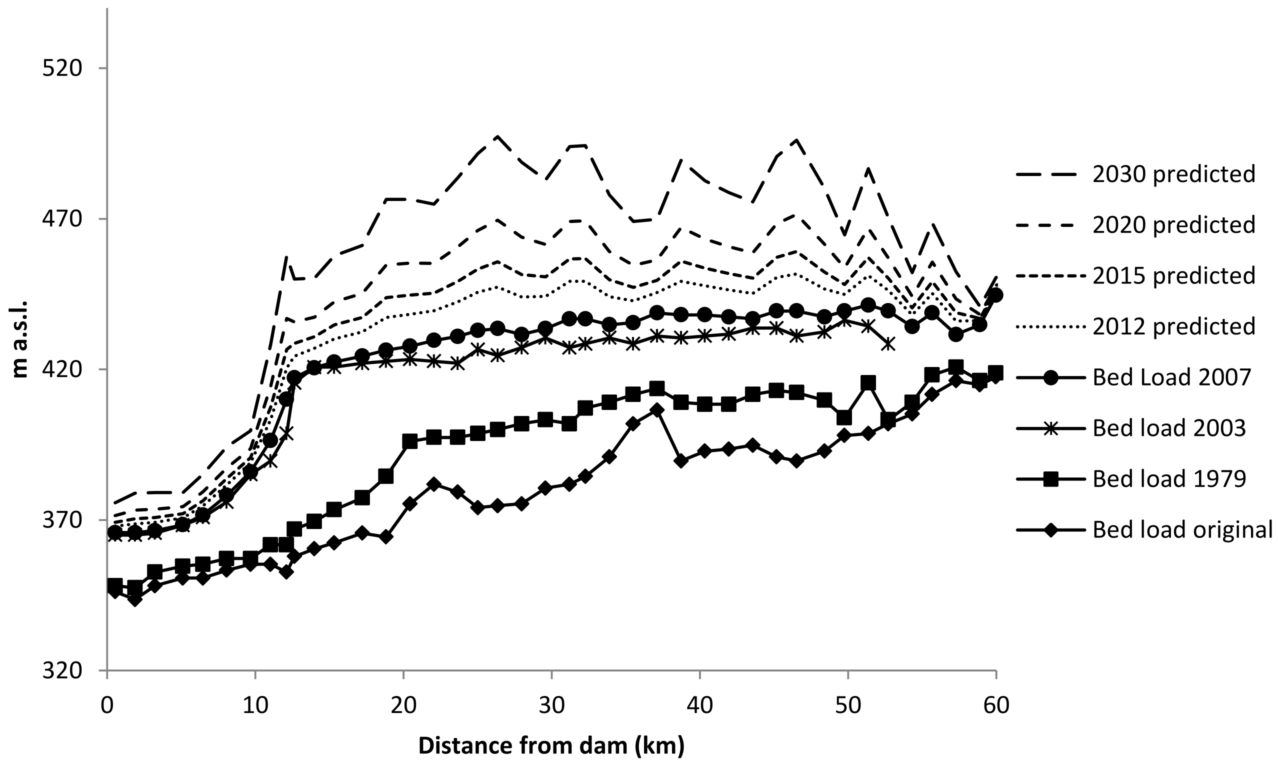


Figure 59: Cross section of Tarbela Reservoir showing future predictions of sediment bed load levels given sedimentation rates remain constant.

5. Discussion

In this chapter, the data collected and presented is discussed and critically analysed. Throughout this section, analysis takes place that corresponds directly with the original research objectives of the study. The analysis looks to determine whether findings from this research either support or contradict comparable literature. Results from this research are also analysed to determine how individual and current the study has been with reference to existing knowledge.

The themes discussed in this chapter are chosen based on their potential for prospective study. Each research area has been examined as a significant issue in light of the current environmental, social, and political issues surrounding the development of hydropower in Asia. The author argues that findings from this analysis will add critical depth and accuracy to issues surrounding hydropower in the Himalayas. Greater detail will be added to shortfalls in current literature, increasing respect given to similar research. New avenues for research will also be recognised thanks to the distinct conclusions sourced from this study.

Results from this research will act as a catalyst for further more comprehensive research within the subject area. As a result, a more accurate and extensive understanding of the knowledge that surrounds Himalayan hydropower will be achieved. Finally, within the chapter the importance of the research is discussed and any limitations of the study are examined.

5.1. Population growth, GDP, generation, and consumption

5.1.1. Population and GDP

Population, GDP, generation, and energy consumption are four variables that help to generate an understanding of a regions economic well-being, and energy security. Analysing the relationships between these factors encourages an understanding of the influences that exist between them. The greatest importance in this analysis however relates to the impact that hydropower has within these relationships. As a result, we can generate a better understanding of the level to which hydropower is involved within different areas of a countries development.

The first relationship analysed within this section includes that between population growth and GDP in Pakistan, India, China, and Nepal. Comparing these data sets helps to interpret how population growth has affected economic growth, and how development has influenced population levels.

It is strongly argued that many of Asia's problems are exacerbated by the regions high population growth rates (Siddiqui, 2007). It is also believed that among other factors, Asia's economic development is majorly hampered by the huge number of people to whom it is home (Headey *et al.* 2009). Another obvious impact of high population growth is its negative impact on GDP and poverty levels. According to this understanding, research in this section should show that as population growth increases, GDP levels will reduce. This research however shows that as the population has grown GDP levels have increased exponentially, contradicting existing literature. The research also suggests that in all four countries studied, GDP growth rates increase with population growth. This result may be related to changes in the dependency ratio of countries within Asia. The dependency ratio is a measure showing the number of dependents to the total population. The World Bank (2002) argues that Asia's dependency ratio has been reducing gradually over the past 40 years. In theory this supports increases in productivity within Asian economies and helps increase GDP levels.

It can be understood from figures 19, 20, 21, and 22 that population growth has created economic opportunity within the region. Theory however supports the understanding that population growth strongly discourages increases in GDP. China is a particularly interesting case study within this context thanks to its political constraints over population growth and exponential levels of economic expansion. Siddiqui (2007) argues that high GDP growth rates in countries such as China are amplified in per capita terms by corresponding reductions in population growth. This understanding is supported by figure 21, which shows how an exponential increase in GDP levels in China corresponds directly with a slow in population growth.

Bloom (*et al.* 2001), argues that it is possible for the interaction of economic development and population growth to result in a poverty trap. More recently however Dyson (2010) has argued that a reduction in mortality rates has aided growth as healthier workers enhance economic productivity. Strauss (*et al.* 1998) also supports the theory that reductions in mortality rates fuels innovation.

From analysis of figures 19 to 22, it is possible to construct figure 61 which shows the GDP per capita values for the four countries analysed within this section. This helps gives a more accurate interpretation of how the scale at which economic growth is being felt throughout entire populations.

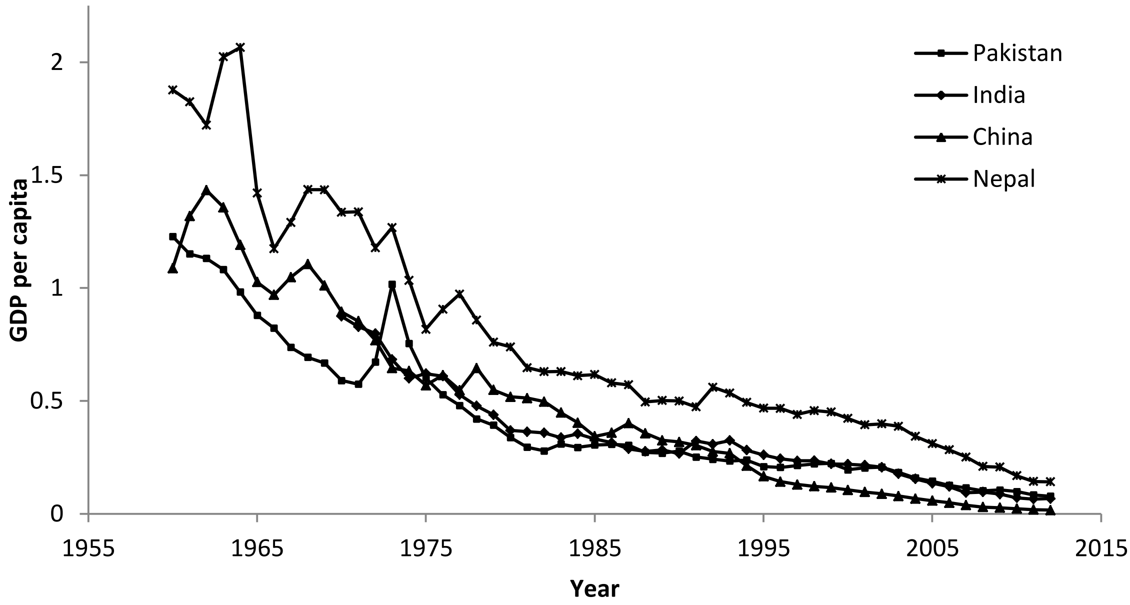


Figure 60: GDP per capita change through time in Pakistan, India, China, and Nepal.

Despite exponential increases in GDP in all four countries, GDP per capita has in fact reduced significantly. This shows that despite the standard of living for many people within these areas increasing, a growing number of people are still suffering below the poverty line. This research supports the understanding that population growth is currently outweighing that of economic growth. As a result, Asian economies are struggling to accommodate such a growth in population, leading to increasing poverty and unemployment issues. Figure 61 therefore supports research by Bloom (*et al.* 2001) and Siddiqui (2007) who argue that poverty is a potential result of the simultaneous occurrence between economic expansion and population growth. It is therefore crucial that population growth rates are controlled within Asia if per capita GDP growth is to be realised. It could be argued that economic expansion cannot possibly accommodate current population growth rates within Asia without political constraint and mitigation.

5.1.2. Population and generation

Population growth has been enabled by the growth in our energy supply. Access to energy allows populations to more effectively survive. In many areas of the world however access to energy represents the greatest opposition with respect to continued population growth. This is where both Malthus and Boserups theories over resource consumption can be analysed in relation to energy supply. Firstly however figures 23 to 26 are analysed to generate a better understanding of the relationship between population growth and energy generation in Pakistan, India, China, and Nepal.

Population growth has already been discussed in this chapter. Its relationship with power generation is particularly interesting however as it relates to the sustainability of current population growth patterns. The greatest difference between the two data sets is the variation in their levels of fluctuation. In all four countries population growth is extremely constant with no inconsistent data points. The data for energy generation however contains far more irregularities that make the data series far less consistent. This may have caused costs and conflicts in relation to providing a reliable source of power as demand for energy is far more constant than its supply. In light of increasing global demand for energy, it is essential that countries within Asia are producing energy at a rate that is similar to population growth rates.

Figure 23 which shows this relationship in Pakistan shows how power generation growth has increased from 1971 to 2006 in an attempt to match the growth rate of its population. Both data sets are strongly correlated. After 2006 however Pakistan's generation performance takes a downturn whilst the country's population growth remains exponential. As a result, Pakistan may have experienced shortfalls in supply, or will have had to increase investment into energy elsewhere in an attempt to meet such deficits. There is abundant literature that refers to a countries carrying capacity in terms of energy. The carrying capacity of an environment is established by the quantity of resources available to the population that inhabits it (Chefurka, 2007). 2006 may represent a time in Pakistan's history that this capacity to provide energy for a growing population has been realised. Malthus's resource consumption theory argues that this conclusion must at some point occur as the regions carrying capacity is overreached. It could also be suggested however that this downturn in generation after 2006 is just temporary with abundant opportunity for recovery.

This relationship viewed in India is relatively similar to that in Pakistan however India's generation growth does not correlate as strongly. India's energy generation growth rate struggles to match that of its population growth until about 2002 when its growth rate increases. There is also no downturn realised after 2006 in India. Generation growth actually continues to grow even further after 2008. This suggests that India still has the potential to increase its supply under huge pressures from population demands.

China is slightly different to both Pakistan and India as its population growth has begun to slow over more recent years thanks to political constraint and a more developed and mature economy. China's generation supply is also far different to that of both Pakistan's and India's. China's rate of generation growth is far less than that of population growth up until roughly 1999 when it exponentially increases. This increase in fact coincides with China's slow in population growth. The correlation between the two data sets is the weakest in the case of China compared with all three other case studies. This figure also suggests that Chinas potential to produce an exponentially increasing supply of energy to its people is huge. Figure 25 shows no signs that energy generation in China is to begin slowing. Reductions in Chinas capacity to produce energy would however represent less of issue for the region than in any other studied. This is thanks to its enormous financial capabilities and capacity to source alternatively. Chinas population is also experiencing reductions in its growth which will help reduce pressures; however concerns of increased per capita demands will have the opposite effect.

The relationship between population growth and energy generation in Nepal is also extremely similar to that in Pakistan and India. Population growth represents a sustained growth from the start, whilst energy generation starts slowly and becomes more exponential with time. The generation data set in Nepal shows the greatest level of fluctuation than in any of the countries studied. This suggests that Nepal's energy supply is the most inconsistent of those researched. These fluctuations are particularly apparent from 1988 to 1998. Since this occurred the growth in generation has been exponential in an attempt to match that of Nepal's population growth. The relationship between these two factors is extremely important, particularly in Nepal. If a country does not have the generating potential to meet continuous population growth then it must rely on supply from elsewhere. This is particularly an issue within Nepal however. Nepal does not possess the capital to diversify its energy needs thanks to its more traditional economy and lack of financial capacity. Chefurka (2007) explains how the extent to which a country can survive a reduction in energy supply depends on whether they have other consumption they can forego to allow them to pay for the energy they require. Countries such as Nepal at the bottom of the economic ladder haven't got the ability to relocate their discretionary spending for this purpose. As a result, they will be outbid in attempts to source fuel alternatively.

It is clear from figures 23 to 26 that energy generation has increased exponentially through time in an attempt to meet growing demands caused by rapidly growing populations. To get a better idea of how successful these attempts have been to meet growing demand figure 27 has been constructed to generate an understanding of generation per capita. This can be seen below as figure 62.

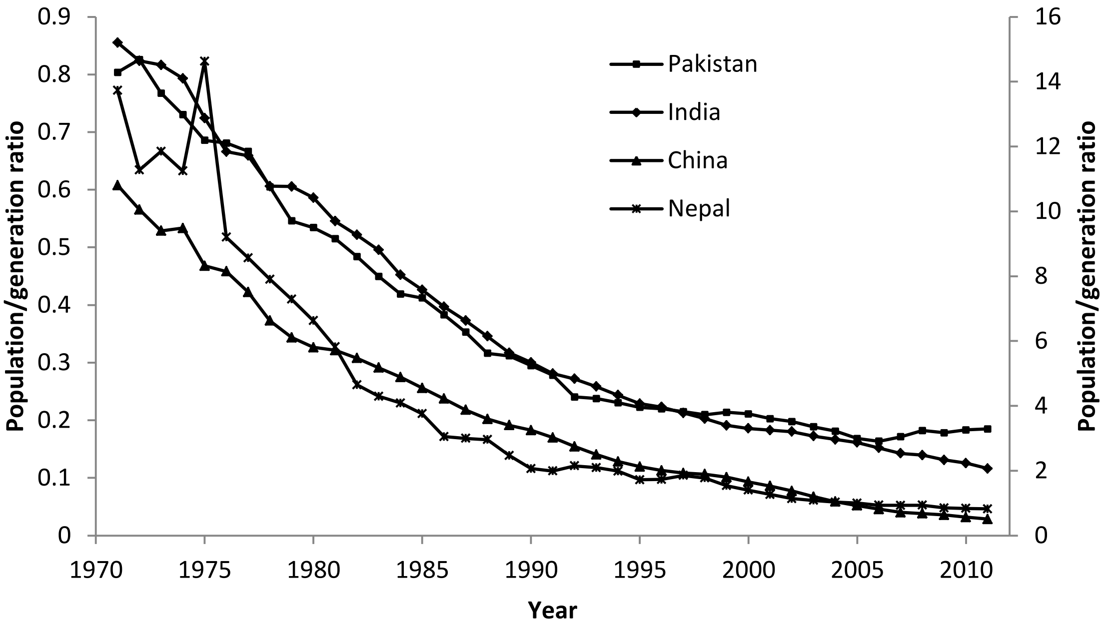


Figure 61: Generation per capita change in Pakistan, India, China, and Nepal (Note the change in scale for Nepal).

Despite the growth in energy generation becoming more exponential in recent years figure 62 clearly indicates that for all four countries generation per capita has fallen significantly over the past 40 years. This suggests then that despite large efforts, production of energy has not been able to compete with the scale at which populations are growing within Asia. As a result, each individual in the region has now got access to less energy that they had previously. This is a particularly concerning result when understanding that per capita demands for energy are also on the increase. As a result, it is likely that these countries are having to increase investment from abroad in an attempt to limit shortfalls in supply. This puts greater pressure on the economies of these countries and threatens their energy security.

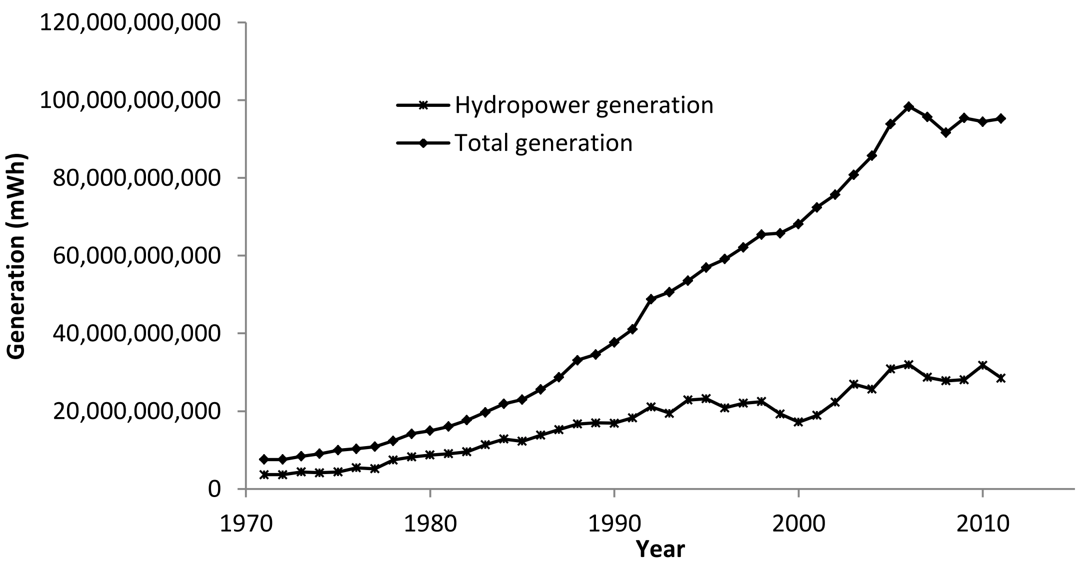
5.2. Hydropower and total generation

Countries in Asia are beginning to increasingly invest their time and money into hydropower as it becomes a progressively more respected and valued alternative source of energy. This is being driven particularly by developed regions attempting to diversify their energy supplies. Energy diversity translates as an indicator of energy security. The greater a countries reliance on a single energy source, the greater its security issues are in terms of a consistent supply. Heavy reliance on hydropower can therefore be understood to be a high risk strategy despite its renewable and sustainable image.

The capacity to develop hydropower along Himalayan Rivers is enormous. Nepal in particular has huge untapped potential thanks to its hostile location and incapacity to finance developments. Experts have indicated that Nepal needs to improve cooperation with technologically advanced countries like India to capitalise on its hydrological reserves (Meeking, 2013). Cooperation between these regions has been constrained however by historical and political antagonism.

This area of research is looking to analyse how reliant each country is on the power sourced from hydropower. This is a particularly important area of research in the current political and environmental climate as the feasibility of hydropower comes under scrutiny. Figures 23 to 26 show the scale to which hydropower contributes towards each country's total output. Analysing these two data sets gives a strong indication of the countries dependence on hydropower. Along with energy security issues, each countries attitudes towards carbon emissions can be roughly drawn from these figures.

To more easily interpret this relationship, a more focused view of the data is shown below. Figure 63 shows only the relationships between hydropower and total generation within each of the four countries analysed. This also gives an opportunity for easier comparisons to be made between countries.



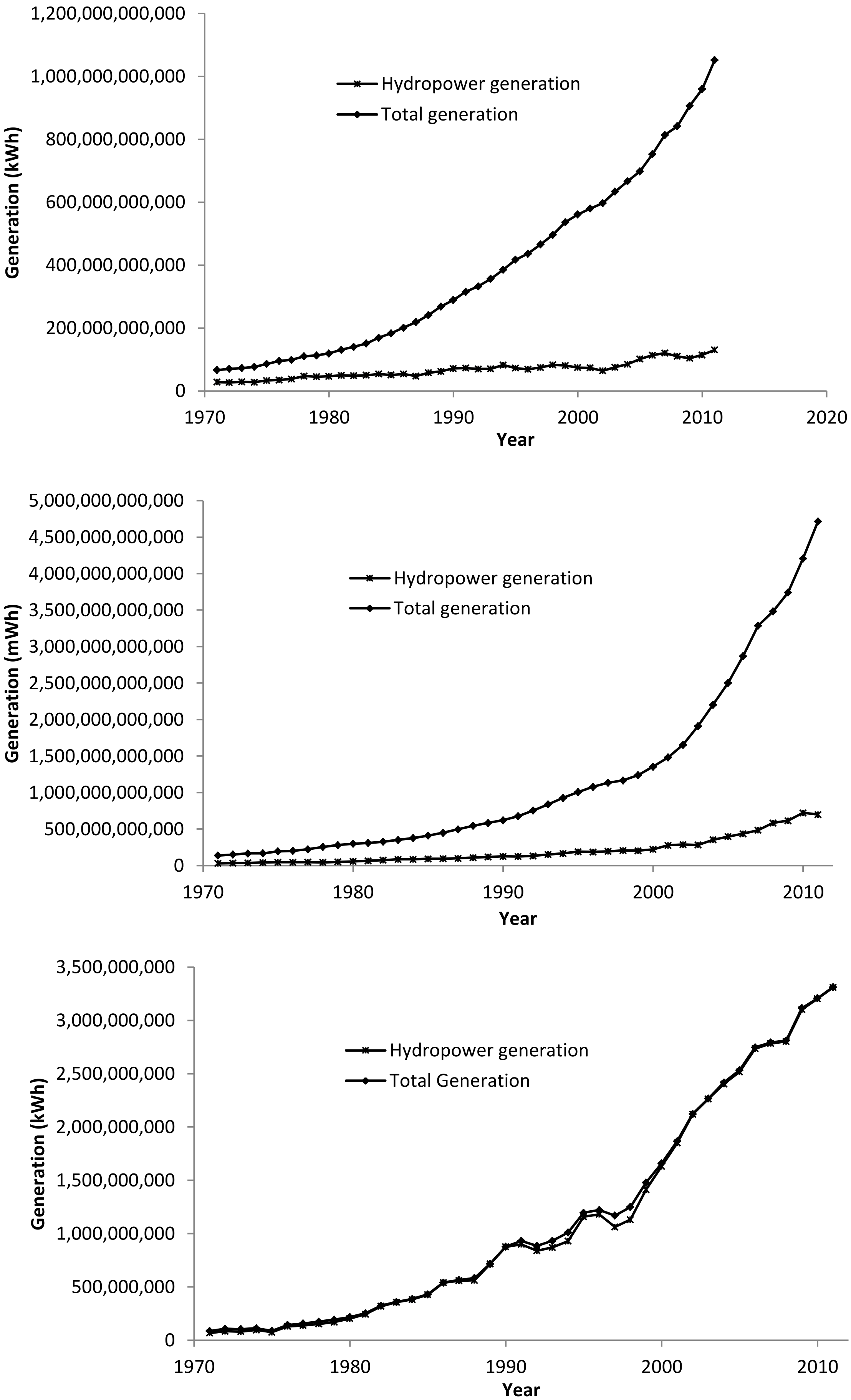


Figure 62: The relationship between hydropower and total generation in Pakistan, India, China, and Nepal.

Figure 23 shows how Pakistan's dependence on hydropower has changed through time. Total generation has increased exponentially in Pakistan since 1971. Hydropower has also increased significantly, however its rate of growth is considerably less than that of the total. This is clearly expected to occur, however the scale of this difference is potentially surprising. In Pakistan hydropower contributes a relatively large percentage towards the total output, particularly in comparison to China and India. In 1971 hydropower represented 48.6% of Pakistan's total electricity output. In 2011 however, hydropower represented just 29.9% of total electricity output. Although still significant, this reduction in scale of contribution is particularly surprising given the high levels of political focus and investment that has been associated with hydropower more recently. Figure 23 shows that Pakistan now relies more on alternative sources and also shows the scale to which these have been exploited in comparison to hydropower. Figure 63 suggests that fossil fuels are now being further exploited to meet growing demand in Pakistan, which threatens to reduce the feasibility of existing hydropower projects. In an attempt to reduce Pakistan's reliance on fossil fuels the National Water Resource and Hydropower Development Programme Vision 2025 has been developed. The plan aims to provide the region with cheap renewable electricity that compensates for predicted climate changes (UNIDO, 2013). This programme is fuelled by the understanding that only 15% of Pakistan's hydropower potential has been harnessed to date. This is potentially encouraging; however it could also be cause for concern as a lack of development indicates that externalities are preventing investment from occurring.

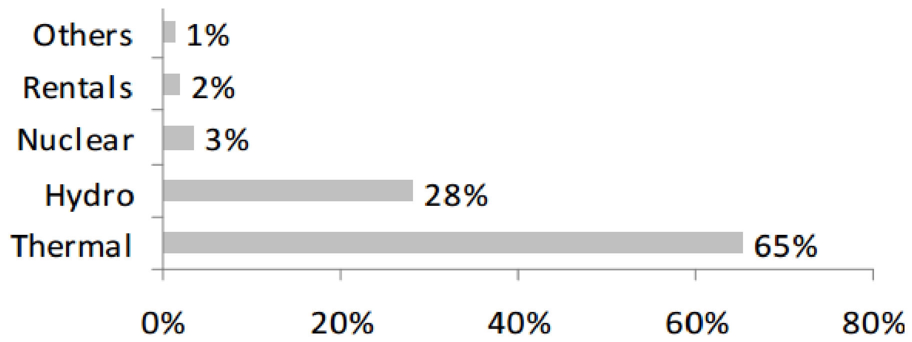


Figure 63: Electricity generation in Pakistan (UNIDO, 2013).

Figure 24 shows India's reliance on hydropower as a source of power. Power shortages are recognised as India's greatest obstacle to economic development. Poor electricity supply increases the cost of doing business in India, reducing productivity, and hampering the development of industry and commerce (World Bank, 2012). The government of India has set a target for India's optimum power system mix at 40% hydropower (World Bank, 2012).

Figure 24 shows that India's total generation has increased exponentially, whilst the countries hydroelectric generation increase is more reasonable. Hydropower in India now represents a far smaller percentage of total generation than it ever has done. This is surprising given the growing interest relating to India's hydropower potential. In 2011 hydropower only represented 12.4% of total generation in India. This is a sharp decrease considering hydropower represented 42.2% of India's total generation in just 1971. This proves the exponential scale to which other energy sources have been exploited to meet growing demand. India relies heavily on coal based thermal energy for its power (World Bank, 2012). Hydropower has shown signs of an increased rate of growth since 2002 however high levels of investment will have to occur if hydropower is to become a significant contributor toward the Indian energy sector. India is however looking to develop its hydropower opportunities with engagement from the World Bank. In November 2014 for example, India signed a contract with Nepal worth $1billion that agreed the construction of a 900 megawatt hydropower project along Nepal's Arun River (Yahoo, 2014). Current trends shown in figure 24 however suggest that alternative sources are set to further outweigh hydropower's contribution despite investment.

The relationship between hydropower and total generation in China is shown in figure 25. Heavy and hazardous smog in major cities has put the government under severe pressure to ease Chinas dependence on coal (Stanway, 2014). China is already the biggest hydropower producer and is on course to exceed a target to raise its hydro capacity. A slowdown in project approvals however means it is behind on its longer term goals (Stanway, 2014). Figure 25 shows an exceptional rate of growth concerning Chinas total generated power. This is however expected due to Chinas huge levels of economic growth. Hydropower has not grown at anywhere near the level to which total generation has, despite an increase in its rate of growth since 2002. Hydroelectric generation growth rates more recently show Chinas intensions for investment. Stanway (2014) would however argue that this increasing trend is unlikely to continue as a result of a reduction in the number of dams getting commissioned. It is clear from figure 25 that China still relies heavily on coal to fuel its economic growth. There are a number of major projects in the pipeline; however the scale of Chinas increasing demand for fuel will inevitably continue to reduce hydropower's significance in relation to its entire supply line.

This relationship is very different in Nepal in comparison to the previous three countries. Nepal is now making enormous efforts to start exploiting the untapped hydropower resources of its Himalayans Rivers. Only last year Nepal launched a hydropower growth plan which included a $1.4billion project on the upper Karnali River (Mallet, 2014). Figure 26 shows just how reliant Nepal is on hydropower as an energy source. Maxwell (2012) also explains how Nepal relies on hydropower for its base load, resulting in a disparity of power supply. Figure 26 shows that both data sets almost mirror each other completely ignoring a period between 1986 and 2000 where hydropower's share hold fell slightly. Nepal's total generation data is also the most variable in terms of fluctuations. This is likely to be the result of hydropower having a greater impact over the countries total generation than in any other region analysed. Figure 26 therefore suggests that a greater reliance on hydropower results in a more inconsistent supply of electricity. It is clear from figure 26 that Nepal's reliance on hydropower is extremely high. In fact for the entire time period analysed, hydropower almost mirrors that of total generation perfectly. This leaves Nepal in a precarious position in terms of future energy security concerns as speculations are continuing to be made regarding hydropower's sustainability.

To getter a better understanding of how a countries reliance on hydropower has changed through time, the ratio between these two data sets is shown in figure 27. This allows for a more focused understanding of hydropower's contribution toward each countries total generation. This can be seen in figure 65.

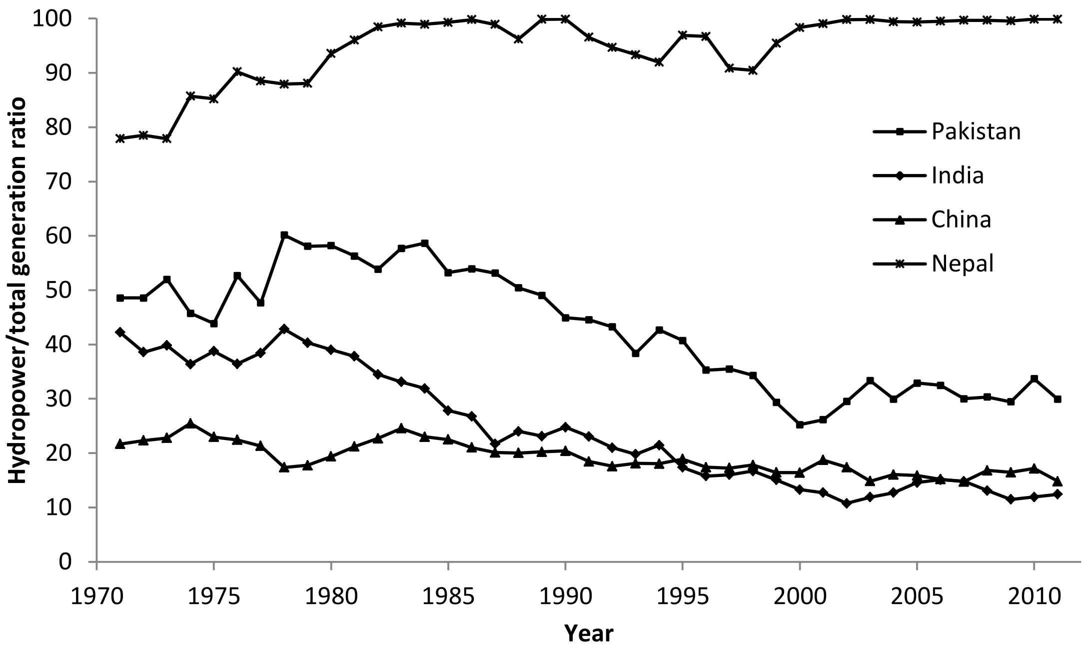


Figure 64: The change in the ratio of hydropower to total generation in Pakistan, India, China, and Nepal.

Despite growing interest over hydropower as a significant source of sustainable power in South Asia and an increasing level of exploitation, the common trend in the region shows hydropower's decreasing significance. In Pakistan, India, and China, hydropower's impact on total generation reduces. In India for example, hydropower's contribution fell by 29.8% over a 40 year period. This is a huge reduction, particularly when appreciating that hydropower capacity in India has increased by 466% from 1971 to 2011. This gives an indication of the scale in which other resources have been further exploited to help meet demand. Hydropower's significance in China and Pakistan also reduces, however at a smaller rate than that in India. India's large scale reduction may be related to failing cooperation with Nepal, as the majority of India's potential for hydropower relies on agreements with Nepal for a stake in its natural resources.

The hydropower to total generation ratio in Nepal is very different to the other three countries discussed. From 1971 to 2011, hydropower's influence over Nepal's total generation has increased from 77.9% to 99.9%. This is an advantage in terms of Nepal's carbon footprint and environmental impact. It also shows that Nepal's attempts to further exploit its resources are proving successful, and its reliance on fossil fuels are also reducing. Adhikari (2013) explains how Nepal is yet to tap even 1% of its hydropower capacity with 60% of its population still deprived of electricity. This would suggest that Nepal's almost complete dependence on the resource is unsustainable as it struggles to supply less than half of the population independently. Nepal's high dependence is due to its access to natural resources and also its incapacity to source power from elsewhere. Financial investment from India is aiding Nepal's attempts to further utilise its hydroelectric potential. This is however further increasing Nepal's dependence on the resource. It is obvious that Nepal has the most to lose in terms of worries over future hydropower efficiency. Nepal has no energy alternatives if hydropower begins to reduce in efficiency however. Poor production figures would also reduce future investment from India as the feasibility of projects begins to reduce.

If poor productivity becomes more greatly realised in the future, it is likely that trends in Pakistan, India, and China shown in figure 65 will continue. As a result each countries energy strategy will increasingly include fossil fuels to help cover shortfalls in supply. This can be viewed as another 'tragedy of the commons' whereby an increase in the use of fossil fuels to meet shortfalls in supply will cause increased productivity issues in terms of hydropower generation.

5.3. Existing hydropower efficiency

In an attempt to understand hydropower's potential as a sustainable investment, current performance trends within the industry have been analysed. Productivity figures are shown in figures 33, 34, and 35 from the River Sutlej, Chenab, and Indus respectively. Current trends shown in these figures can help determine future patterns of hydropower performance. Data such as this can be appreciated as a prerequisite for future successful investment.

Current trends shown in these three rivers indicate that hydropower efficiency has reduced within current projects over the last 30 years. The data also shows high levels of fluctuation in all figures, threatening a consistent supply of power to regions within South Asia. This volatility is particularly demonstrated along the River Sutlej with generation halving over just a six year period between 1999 and 2005 for example. Irregularity such as that in figure 33 supports research by Jeuland (*et al.* 2013) who argues that climate variability in the Himalayas is causing irregular generation figures. This relationship is further supported by Laghari's (2013) argument that a 1% reduction in stream flow causes a 3% reduction in output. Shah (*et al.* 2011) also argues that these strong fluctuations shown in figures 33, 34, and 35 are a result of South Asia lack of water storage capacity, as rivers don't have the infrastructure to control flow rates during periods of drought and flood.

These three figures completely discourage the understanding that hydropower is a sustainable and economic alternative to more commonly exploited fossil fuels in South Asia. The enormous start-up costs associated with hydropower make its productivity crucial in relation to each projects pay-back period. Reductions in the efficiency of projects as shown in figures 33, 34, and 35 help to prolong the length of time it takes a project to payback its initial cost of construction. This is particularly concerning for projects that have been subsidised by FDI with specific dates for repayment.

Despite a negative overall change in performance, the River Chenab has more recently shown a recovery in its performance figures. This is dissimilar to results shown along the River Sutlej and River Indus, both of which show a more constant decrease despite fluctuation. The River Chenab's results past 1995 could be supported by research by Collins (2008) who explains how realisation of the de-glaciation discharge dividend will first result in an increase in runoff (due to climate change) before reductions in glacial mass balance bring reduced flow to local catchments, which within this case study has not yet been reached. Within figures 33 and 35 however reductions in hydroelectric generation which directly relates to river discharge may already be experiencing reductions in the glacial mass balance that supplies the majority of their flow.

It is firstly important to dismiss any argument toward the belief that reductions in the hydropower performances shown are intended. No benefits could be drawn from intentionally slowing the output from hydropower. Hydropower has extremely low running costs, small environmental impact, and benefits relating to both food and water security. In a region that is also experiencing exponential increases in demand for energy, a decision to reduce the output from hydroelectric sources would be nonsensical, despite smaller fears over social impacts. As a result, a range of negative externalities are strongly believed to be encouraging the results shown in figures 33, 34, and 35.

The most well established argument for current reductions in hydropower performance however relates to the theory of sedimentation. This theory is strongly supported throughout modern literature (McCully, 1996; Frenette *et al.* 1996; Abbas *et al.* 2012; etc). Sedimentation reduces a dam's capacity to store water, reducing its ability to generate electricity so efficiently. This reduces consistencies in its supply, potentially explaining the fluctuations shown along the three rivers. This also increases reliance on the Himalayan climate as each dam has less capacity to control its river flow rates.

The results shown in these figures have potentially influenced the results shown in figures 63 and 65. Reductions in productivity rates are potentially a major contributor towards hydropower now contributing less towards South Asia's total electricity output despite growing investment. Current productivity trends represent a major concern for political figures evaluating the feasibility of future investment within the industry. Results from this research would strongly suggest that further investment into hydropower within this particular region would prove unsustainable and uneconomic.

5.4. Impacts of climate change

Climate change contributes significantly to many of the negative externalities associated with the feasibility of hydropower. This is because climate change has the potential to influence changes in river properties through encouraging variations in hydro-meteorological conditions. These river properties include discharge and sediment concentration for example. Changes in river runoff pose the greatest threat to hydroelectric generation. This is because hydropower performance relates directly to the consistency and magnitude of the runoff it requires.

The analysis of figures 36 to 41 helps to determine the level of impact being realised on hydropower in South Asia with respect to changing patterns of river runoff and weather conditions. Figure 21 shows that from 1971 to 2002, river discharge from the river Sutlej at Khab gauging station has decreased considerably. A maximum runoff of over 10,000 10^6m^3 in 1973 is followed by a minimum of 2485 10^6m^3 in 2001. This reduction is considerable, particularly when considering the short time period. The volatility of this change has the potential to have serious implications for water storage and hydropower within the catchment. Research by Laghari (2013) suggests that changes in hydroelectric generation are 3 times greater than changes realised in river runoff. This is particularly concerning when understanding that there has been roughly an 80% reduction in stream flow at this station over the 28 year period between 1973 and 2001. The large fluctuations shown in figure 36 also show the variability in which annual runoff is occurring. This variability relates to the seasonality of rainfall and the impacts of the South Asian monsoon. Dharmadhikary (2008) explains how the monsoon delivers 80% of annual rainfall in June-August. This understanding corresponds with the fluctuations shown in figure 21 as a heavy reliance on rainfall from just a short period of time encourages large inconsistencies in annual runoff. This is concerning when appreciating the more constant and persistent annual demand for electricity in South Asia.

A very similar pattern of stream flow reduction can be appreciated by analysing the change in runoff from Rampur gauging station. Runoff volume is greater at Rampur thanks to its more downstream location. These results are shown in figure 38 and show how river discharge increases slightly from roughly 1964 to 1983. After this data point however, discharge begins to mirror that of figure 36 and reduces substantially. The IPCC (1998) would argue that this original increase in runoff is the result of increased rainfall as they predict a 15% increase in precipitation levels. It could also be argued however that this increase is the result of increased glacial melt due to rising global temperatures. This understanding would also correspond with literature from the IPCC (1998) which explains how global mean temperatures will rise by 3°C by the end of the century. The succeeding reduction in discharge is then potentially the result of reduced mass balance resulting in reduced glacial melt water. This argument supports literature by Collins (2008), who suggests that the de-glaciation discharge dividend will influence an initial increase in runoff followed by future declines.

The high frequency and magnitude of fluctuation within both of these figures threatens to damage the efficiency of hydropower along this catchment. Hydropower requires a consistent supply of runoff to operate capably, however the seasonality of rainfall and glacial melt makes consistency difficult to establish. This is particularly the case along catchments that have failed to develop sufficient water storage capacity. Demand for the resource is also increasing consistently, which puts added pressure on productivity as increases in supply struggles to match that of demand. It is therefore likely that periods of reduced river discharge, and therefore reduced hydroelectric output will have to be increasingly supported by input from fossil fuels. Moors (et al. 2011) suggests that climate change will influence greater variability in discharge. This is not supported by either figure 38 or figure 40 however as fluctuations and variations in runoff has remained similar throughout. It could even be argued that variations have reduced with reductions in overall discharge at both stations.

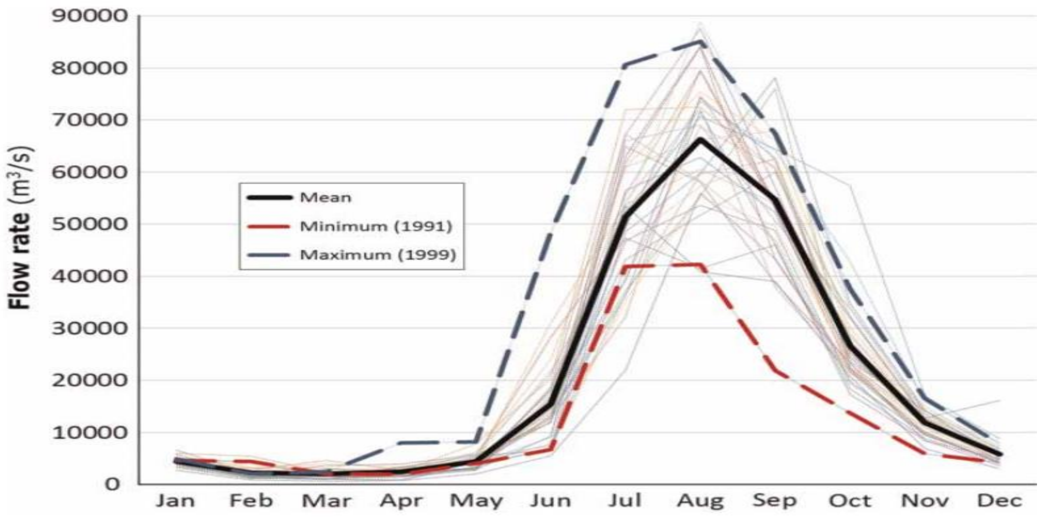
Along with understanding how the volume of runoff has changed through time, research has also taken place that looks into how the timing of runoff has altered. Figures 37 and 39 look at how the timing of maximum discharge has changed through time at Khab and Rampur gauging stations respectively. Both are very similar with respect to significant falls in maximum discharge through time. The greatest change in runoff is realised during the summer months between April and September as this is when the majority of runoff takes place. Months either side of this summer period see very little runoff. This finding complements research by Jeuland (2013), who explains how flows from January to May comprise only 6% of total annual flow along Himalayan rivers.

Literature suggests that as a result of climate change, runoff is now likely to peak before the main growing season, making the supply of water less efficient (Wilson, 2011). In

South Asia there are two main growing seasons. The Kharif season occurs from July to October, whilst the Rabi growing season is from October to March (Arthapedia, 2011). Figure 37 shows that in 1973 when the greatest annual discharge occurred, maximum discharge occurs in June. Maximum discharge in 2001 however is far less substantial and occurs one month later in July. This change means that discharge now coincides more accurately with the start of Kharif. This research contradicts current literature by Wilson (2011), who suggests that with time maximum discharge would occur earlier as a result of climate change, impacting on crop yields. Findings from figure 39 which shows the same relationship at Rampur station are very similar to those shown in figure 37. This figure also contradicts that of Wilson (2011) as maximum discharge occurs later in the year through time. Despite maximum runoff now coinciding more accurately with Kharif, the reduced level off runoff creates greater concern with respect to both power and food security in the region. This finding really supports arguments for greater water storage capacity in the region; particularly as current trends suggest that river discharge will continue reduce annually.

Figure 66 shows a comparison between the discharge of the Ganges River (a) and the river Sutlej (b). The figure is made up of a graph taken from existing literature and one that has been constructed during this thesis's research. It is immediately apparent that runoff occurs earlier in the year within the river Sutlej compared with the Ganges River. Graph (a) shows that through time runoff has increased considerably. This potentially supports Collins (2008) theory of an initial increase in runoff due to increases in melt water. This is completely the opposite of that shown in (b) which displays a substantial decrease in discharge through time. Both graphs however show that with time, maximum discharge is occurring later in the year, benefiting the Kharif growing season as a greater percentage of the discharge can be utilised. This finding shows that Wilsons (2011), theory is completely inaccurate with respect to South Asian Rivers. Substantial reductions in discharge within the River Sutlej however are likely to cause problems for irrigation, particularly as the majority of runoff reduction occurs within the summer months, when energy is in particularly high demand for cooling purposes.

a.



b.

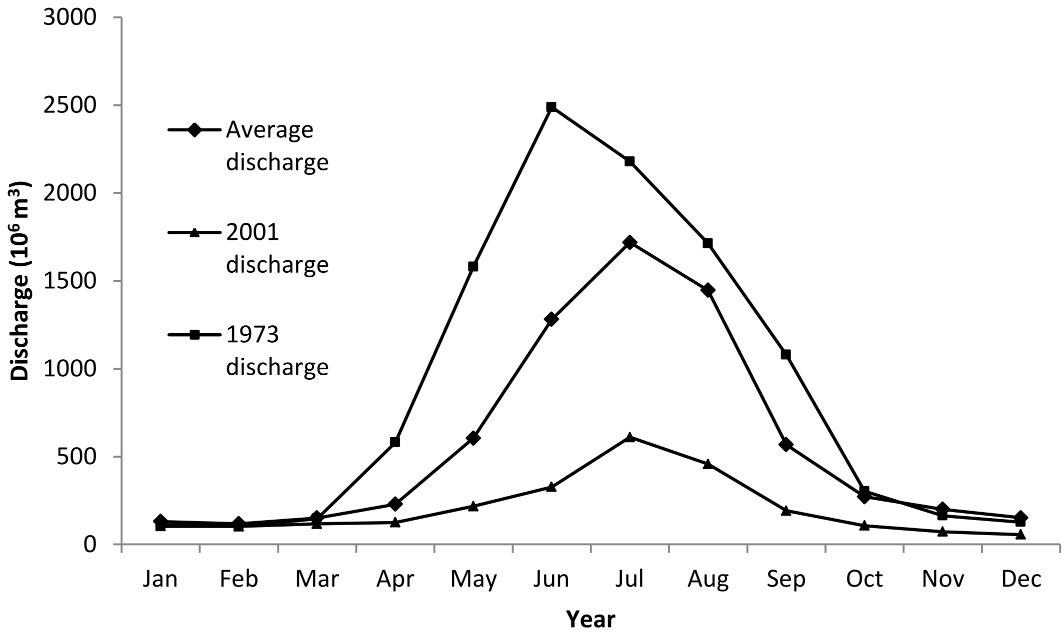


Figure 65: Comparison between the change in timing of discharge at (a.) Farakka barrage along the Ganges River (existing research) and (b.) Khab gauging station along the River Sutlej (current research).

Climate change influences externalities that arguably have the greatest influence over hydropower's productivity. As a result, analysing both air temperature and precipitation levels locally will facilitate an understanding of hydropower's vulnerability toward changes in hydro-meteorological conditions. Figures 45 and 46 show fluctuations in precipitation and air temperature levels respectively within the River Sutlej basin. Despite large fluctuations, precipitation surrounding the basin remains stationary over the 101 year period. It could be argued therefore that precipitation bares no correlation to runoff in the basin. This is however unlikely as it is strongly argued within current literature that precipitation strongly influences Himalayan river runoff (Harrison *et al.* 2012; Collins, 2013; Hamududu *et al.* 2012; etc). Figure 40 however doesn't determine the precipitations composition. Precipitation falling as snow contributes towards glacial mass balance, freezing and a small volume of runoff. Rainfall contributes directly to river runoff, particularly after ground saturation. Changes in the ratio of snow and rainfall will alter runoff significantly, upsetting a balanced supply of fresh water to communities and businesses in downstream locations. The volatility of the fluctuations within figure 40 is also a concern as this will considerably contribute toward disturbing hydropower's consistent productivity. Figure 40 suggests however that the volatility of precipitation patterns is not increasing; contradicting what is argued in current literature (Moors *et al.* 2011). Due to the lack of overall change in volume of the regions precipitation levels it could be argued that other factors influence runoff more significantly. These may include increased river development, irrigation demands, and changes in the rate of snow and glacial melt, disrupting river discharge.

Figure 41 encourages the understanding that air temperature is contributing towards changing patterns of river runoff. Figure 41 shows that air temperature surrounding the River Sutlej has increased from 1901 to 2002. Increased temperatures would encourage greater snow and glacial melt, increasing runoff initially, however reducing glacial mass balance in the long term. This finding supports literature by Collins (2008) who founded the theory of the deglaciation discharge dividend. The figure however only shows a very small overall increase despite large fluctuations throughout the data set. From the lowest recorded data point in 1917, air temperatures increase by 2.75°C up to its highest recorded data point in 1999. This increase may seem small however its significance will be far greater due to the Himalayas more hostile environment. This change in temperature will influence large changes in the composition of precipitation, therefore impacting largely on local annual river runoff directly impacting the productivity of local hydropower initiatives. Increased snow and glacial melt will also reduce the albedo effect of the Himalayan region as less of the sun energy gets reflected away from the earth's surface. Instead more of the suns energy will contribute towards further rising air temperatures in the region. Measuring future glacial melt in the Himalayas is particularly important due to its worldwide impact. Increased glacial melt, contributes toward worldwide sea level rise which puts low lying regions under pressure. Unfortunately, many of the regions vulnerable to sea level rise have made very little contribution to the temperature change being realised.

5.5. Evolving dam and hydropower development

This section of analysis relates to how the development of hydropower has evolved in India through time as a result of externalities. Figures 42 to 45 help explain how the development of hydropower has had to change in an attempt to become more feasible and sustainable. During this research the five states of India that border the Himalayas were chosen as suitable case studies. Figure 42 shows the number of dams built in these 5 states of India during certain periods of time. The results show that the majority of dams were built between 1971 and 1990, with 1,296 dams being built in the years between 1971 and 1980. Before and after this period however the number of dams built is far less significant. This result corresponds with the results shown in figure 28 which shows how the ratio of hydropower to total generation increases during the same period of time and then declines once development levels reduced shortly afterwards.

The number of dams constructed in this region of India decreases significantly after 1990. This could be the result of a number of reasons. These include a lack of space along certain river systems due to the magnitude of development that has already occurred. A lack of space could also be caused by growing populations that are now more frequently settling within areas alongside river systems, due to overcrowding elsewhere. This makes development along Himalayan rivers more difficult as a greater number of people are faced with the potential negative impacts, increasing opposition. Greater opposition will also be created as the environmental impacts of hydropower become more understood. Greater research into hydropower has meant that people are now more educated on the negative externalities of hydropower. This is now making it more difficult for developments to be approved as powerful political figures now have a greater understanding of its impacts. The high level of infrastructure that is already present along the majority of Himalayan rivers is leading to the feasibility of many of the projects to be reduced. This relates to developments having an impact on the natural flow of water, reducing the rate at which electricity can be generated. Countries are not going to invest in a project that becomes less economically feasible with time due to impacts of climate change and overdevelopment.

Figure 43 shows the number of dams that have been built in each of the five states of India studied. This information is interesting in that it shows how well developed each of the river systems is and gives an indication of their capacity to generate power. This figure can also show which rivers have potentially been underdeveloped and where further investment could potentially be feasible.

Figure 44 shows the size of the dams that have been constructed within these 5 states of India. The majority of dams within this region have a storage capacity of up to 100,000 10^3m^3. Dams larger than this are infrequent. This is because smaller dams are now recognised by political figures as being kinder to the environment. This makes them a more feasible investment despite not being able to compete with larger infrastructure in terms of generating output. This may also explain the greater frequency of smaller dams, as multiple small dams are needed to match the generating potential of one single large development. The start-up costs of hydropower are also notoriously high, which makes large scale developments particularly straining financially. Smaller developments are potentially becoming more desirable as they require less capital initially.

How the size of dams has changed through time can be interpreted through analysing figure 45. Figure 45 shows the relationship between a dam's size and its year of construction. This relationship is important as it helps explain how dam size has changed through time. This relates to how development has evolved in light of externalities. Results from figure 45 indicate that the size of dams being built in this region of India are getting smaller with time. This has occurred despite the technology being available to build dams even bigger than in previous years. This understanding is potentially the result of concerns over environmental impacts influencing less controversial developments. There may also simply be limited space available for large developments, making smaller ones more convenient. Smaller dams are also less impacted by the threats of climate change, making their development instantly less feasible. It now appears that building a higher quantity of small dams rather than one mega dam is a far more sustainable direction of development. Only building smaller dams however may cause pressures in relation to not generating high levels of electricity. Dams with smaller storage capacities have less potential to generate hydroelectric power. Shortfalls in energy are therefore likely to be met by other, probably unrenewable sources, potentially worsening externalities caused by climate change. They are also less capable of storing high volumes of water which threatens the regions water security.

Despite this trend toward micro hydropower as a result of environmental pressures, it is likely that future growing demands for energy will outweigh the need for environmental responsiveness. As a result, it is likely that in the future mega hydropower stations will be built in an attempt to increase generation potential significantly despite concerns over environmental factors. Energy demands will always take priority over environmental factors due to their influence over economic growth.

5.6. Effects of sedimentation on reservoir efficiency

Sedimentation is the greatest natural phenomenon to threaten the longevity of dam operation. This is increasingly becoming the case, as the impacts of climate change threaten to increase the scale at which sedimentation is realised within South Asian reservoirs. These impacts relate to greater variability in weather conditions, increased glacial melt due to higher air temperatures and greater levels of river development and erosion. Population pressures are also recognised as a large threat to dam operation and efficiency, thanks to deforestation, agriculture and the development of river side infrastructure. Sedimentation causes a range of different problems that threaten the overall economic feasibility of an investment into hydropower.

Theory suggests that sedimentation is going to increase significantly with climate change (Munir, 2011). Tarbela Reservoir was used as a case study to interpret the real impact of sedimentation on one of the largest and most significant dams in South Asia. This dam is of particular interest due to its vulnerability to climate change and its significance in terms of Pakistan's water and energy future. A significant proportion of the runoff that reaches Tarbela is meltwater. Runoff reaching Tarbela is also subject to monsoon rainfall during July, August, and September (Ali *et al.* 2007). These factors along with tectonic instability in the region, and high degradation rates puts Tarbela reservoir at extreme risk from impacts associated with high sediment levels.

Figure 46 shows annual discharge levels at Tarbela reservoir from 1962 to 2009. Despite large fluctuations in the data series, overall discharge levels remain constant for this 47 year period. This finding contradicts that of Harrison (*et al.* 2012), who explains in figure 3 that climate change will encourage reduced runoff as precipitation falls as rain rather than snow. Collins (2013) also supports the theory that runoff will decrease thanks to reduced summer precipitation levels and reduced mass balance. The fluctuations shown in this figure also relate to inefficiencies in generating potential as inconsistent flows correlate directly with unreliable production. Figure 47 also shows that despite large fluctuations, overall sediment inflow levels have also remained constant from 1980 to 2012. This finding corresponds directly with the discharge data and as a result, supports literature by Ali (*et al.* 2007), and Munir (2011) who explain that sediment inflow correlates directly with discharge, with few, if any active variables. The understanding that sediment inflow remains constant at Tarbela however contradicts other research by Munir (2011) that suggests climate change is likely to encourage change in relation to sedimentation. Figure 47 suggests that there has been little change regarding sediment inflow. High levels of annual fluctuation will also make predictions regarding future sedimentation more difficult, as rates become unpredictable. The successful implementation of mitigation strategies is therefore likely to be challenging.

The high frequency and magnitude of fluctuations regarding sediment inflow shown in figure 47 could also support literature by McCully (1996). McCully (1996) explains how fluctuations are often caused by violent weather conditions. Furthermore he explains how the level of sediment inflow that such weather conditions can encourage is exponential. This theory potentially explains why the fluctuations shown in figure 47 are so erratic. Research by Abbas (et al. 2012) also supports the argument that such fluctuations are influenced by weather conditions rather than by anthropogenic disturbance.

Figure 48 shows the relationship between discharge and sediment inflow at Tarbela reservoir. This figure shows that the data sets correlate directly one another, however through time this correlation becomes less accurate. This shows that this relationship is becoming weaker between the two variables, making future predictions on sedimentation more difficult to accurately estimate. It could be suggested therefore that external factors are now having a greater impact on these variables as their usual behaviour becomes irregular. This is likely to be the result of larger pressures and development along the River Indus leading to increased disruption to the natural flow of the river. Climate change, population growth and river side infrastructure all have the potential to heavily disrupt fragile balances and relationships associated with the rivers properties.

Figures 49 to 53 show how the level of sediment has changed in Tarbela reservoir at five different locations. This gives a large insight into how sediment inflow has influenced a change in the reservoirs bed level, resulting in a reduction in the infrastructures storage capacity. Studying this at five different locations gives a more in depth understanding of the phenomenon and could potentially lead to more accurate mitigation strategies being incorporated in the future.

Sedimentation at Tarbela will always threaten the dams operation. Mitigating its impacts is therefore crucial if it remains feasible. Figure 49 shows the rate at which sedimentation has occurred from the dam’s initial construction in 1976 to 2008 at a distance of 1km from the dam wall. At this location sedimentation rates have to be more closely analysed as they pose the greatest threat to the dams operation. This is because sediment poses a threat to turbines and intake pipes that exist within the dam wall. Sediment at this location also greatly threatens the dam's minimum operating level, which is recognised by Sanchez (*et al.* 2008), who explains how this level was increased in 2006. Sedimentation at this location however is only small in comparison to further upstream. This is because the majority of sediment has already been deposited before the water reaches this area of the reservoir. The majority of the sediment gains occur at 28.4km from the dam wall, shown in figure 50. This is because this distance represents the area where the rivers beds pivot point is realised. This is where the majority of deposition takes place i.e. where the rivers carrying capacity is significantly reduced. Figures 51, 52, and 53 all show similar levels of sedimentation.

Reducing the level of sediment inflow is therefore imperative if future operation of the dam is secured. There are however already plans in place to reduce the inflow, through developments upstream of Tarbela along the Indus. Strategies to reduce the sedimentation at Tarbela are explained later in this section.

Figures 54 to 68 show the predicted future levels of sediment within the reservoir. These predictions are based on the understanding that sedimentation rates will remain the same as they are at present. This was identified as the most accurate way to predict such levels given that figure 47 demonstrates that sedimentation rates at Tarbela have remained the same for the past 32 years despite fluctuations. These five figures all show that up to 2030 if mitigation strategies are not heavily incorporated then sedimentation will lead to the dam becoming completely non-operational. This is because at nearly all locations the sediment level completely outreaches the rivers banks. As a result, the storage capacity of the reservoir has completely been lost at these locations. This is potentially devastating in terms of both water and energy security concerns for Pakistan, particularly in light of growing population pressures and demand for energy.

Mitigation strategies have already been proposed to control the rate of sedimentation at Tarbela reservoir. In January 2006 the government of Pakistan announced the decision to construct 5 multipurpose dams in the country over the next 10-12 years (Himalayan Logistic, 2014). These potential constructions include Diamer Bhasha Dam and Dasu Hydropower Project. Both of these projects are planned to be built upstream of Tarbela reservoir and are designed to increase overall generation, reduce sedimentation downstream, improve flood control and increase irrigation potential.

In the first phase of the governments development plans include the construction of Diamer Bhasha Dam. The project is located roughly 315km upstream of Tarbela Dam and will have a maximum height of 270m. The live storage of the project will also be more than 7.89 10^9m^3. It is estimated that that dam will have the capacity to impound 15% of annual flow (Himalayan Logistic, 2014). This is substantial given the magnitude of runoff from the River Indus.

There are a number of benefits associated with the development of Diamer Bhasha Dam. These include:

- Produces 4,500 MW of electricity through hydropower generation;
- Store an extra $10.5km^3$ of water for Pakistan that would be used for irrigation and drinking;
- Extend the life of Tarbela located downstream by 35 years;
- Flood damage control during periods of high runoff;
- Reduction in dependence on thermal power, thus reducing environmental damage and foreign exchange;
- Construction leading to socioeconomic growth and improved living standards.

Within this thesis the most significant benefit associated with the project relates to the direct impact the development will have on the life expectancy of Tarbela reservoir. The threats associated with sedimentation at Tarbela have already been critically documented. Diamer Bhasha Dam in theory has the potential to completely change the rate at which sedimentation is occurring within Tarbela. Bhasha dam will be designed to help draw sediment out of the water so that runoff entering Tarbela downstream is less sediment rich. This will reduce the future rate at which sedimentation is occurring at Tarbela, reducing the rate at which storage capacity is being lost.

Tarbela, Mangla, and Chashma reservoirs have already lost a combined capacity of 5.3MAF due to sedimentation. It is estimated that by 2016 this have increased to 6.6MAF, which almost equals the combined capacity of Mangla and Chashma reservoirs. Due to the stoppage of many substantial storage developments after the commissioning of Tarbela in 1976, sustainability of existing storage in Pakistan is in jeopardy (itmsoil, 2012). As a result, mitigation strategies are needed to increase the efficiency and relieve pressure on existing infrastructure.

There have been difficulties in the developments construction however. Diamer Bhasha dam was planned to be constructed in 2020, however financial matters have forced the project back to be completed in 2037, converting the water crisis into an existential threat to the country (Hasan, 2014). This set back in the development particularly represents a threat to the longevity of Tarbela when referring to figures 53 to 57 of this research. These figures predict the level of sediment within the reservoir in 2030 will already have overreached the boundaries of the reservoir, reducing its capacity almost completely. If this educated estimate is found to be correct then it is clear that strategies to reduce sedimentation will have to be incorporated far before that of 2037.

It is now believed that as a result of financial difficulties associated with the construction of Bhasha dam, the Dasu hydropower project is being given preference, despite concerns over water shortages and floods (Hasan, 2014). Wapda explain how this change in plan has been termed as a strategic blunder being committed by the departments concerned, leaving the country in a famine like situation due to water shortages (Hasan, 2014).

5.7. Importance of the research

The importance of this research relates to increasing the understanding of how effective current hydropower is and it's potential to mitigate many of the water, energy, and food security concerns associated with countries within South Asia. Awareness is also encouraged in relation to the impacts climate change and population growth are having on hydropower development and performance.

Increasing the understanding of how feasible a large scale investment into hydropower could be in South Asia is crucial if cost effective decisions and investments can be made by political figures. Energy security is crucial to sustain economic growth. It is therefore important to ensure the most sustainable and productive method of achieving energy production.

Analysing the productivity of hydropower through time can also be used as an accurate indicator of climate change. Hydropower is affected by climate change as its efficiency is directly related to river runoff. River runoff in the HKH region is extremely vulnerable to the impacts of climate change due to the hostility of the environment. As a result, the greater the number of hydropower developments, the more accurate predictions related to climate change could potentially become.

Analysing the level at which sedimentation is occurring also relates directly to sustainability. Sustainability also relates to the feasibility of hydropower investments. Having an educated understanding of the possible feasibility of a project before construction takes place makes the development initially a more economically sound investment. Information gathered from analysing some of the most developed river systems in the world can also be utilised by governing bodies from elsewhere, particularly if they are looking to invest heavily in the power source. Due to the start-up costs of hydropower being so high, it is imperative that the payback period of the development is accurately estimated so that FDI is kept to a minimum.

Showing how dam development has evolved through the years can also encourage more nations to follow suit, particularly if these changes have been successful. This would help in making worldwide hydropower more efficient and cost effective and could also encourage greater levels of water storage, reducing water and food security concerns. This is particularly crucial in light of growing populations and reduced river runoff. The ability to store water is becoming increasingly important.

Finally, in light of population growth and resultant increased pressures over food, water, and energy, it is imperative that hydropower's potential for growth and productivity is understood. Reliance on hydropower could potentially increase in South Asia as it has done in Nepal due to the level of untapped potential that exists. Pressures over reducing production from non-renewable sources will also encourage further production through hydropower. Increased demand for hydropower should therefore be accompanied by improved research into the power source, particularly in relation to its future potential for increased production.

5.8. Limitations and improvements

Within this thesis there were a number of limitations that threatened the depth in which research was performed and data was collected. The greatest threat to this research related to the number of different locations that data had to be sourced from. This created issues in relation to the depth of the research being shown.

The greatest limitation of this research relates to the lack of data concerning hydropower performance. This thesis originally aimed to include data showing hydropower performance that could be easily compared with data such as sedimentation and runoff. However this data was extremely sparse and the time periods in which it was collected correlated poorly with other data sets.

The hostility of the environment in which data was originally sourced from also made it impossible to source data primarily. This meant that analysis has been made purely on secondary data reducing the depth at which conclusions can be made from. The data used however has been sourced from reliable sources and is in depth enough to produce a critical analysis and accurate conclusions.

If the author was to complete this research again, a few modifications would be made in an attempt to make the research more detailed and prospective. If done again the author would have given more focus to a more specific area of research in an attempt to make the area of study less broad. This would have given that specific research area more depth, as more time and would have been spent researching that specific area.

6. Conclusion

South Asia and Chinas exponential population growth has put increased pressure on the Himalayan regions natural resources. These include water, food, and energy. Growing populations across South Asia have created enhanced resource stress on the Himalayan region as demand for its resources has grown. The larger the population that relies on a resource, the greater its value becomes.

As populations have increased across South Asia and China, economies have also become stronger. GDP growth occurs alongside population growth. Population growth has created opportunity in South Asia and China for enhanced levels of productivity and service industries growth, increasing the regions standard of living. The immense scale of population growth however has led to an uneven change in living standards. Bloom *et al.* (2001) argue that the interaction of economic development and population growth can result in a poverty trap. GDP has increased exponentially throughout South Asia and China. However, GDP per capita has fallen consistently (as shown in figure 61). This result proves that resources within South Asia and China are not currently strong enough to support such a large population. Wealth within the region is clearly not being evenly distributed. Innovative measures must therefore be taken to more effectively utilise the South Asia's assets to successfully accommodate growing populations.

Electricity generation has increased considerably throughout Asia, despite concerns over natural resources, environmental impacts, and social externalities. Electricity generation has grown due to increased demand from booming populations and a growing demand for improved standards of living. Supply however is progressively struggling to keep up with demands. Electricity production per capita throughout South Asia and China reduced significantly between 1970 and 2010 (see figure 67.) This demonstrates the extent to which population growth is outweighing that of electricity generation. In ideal circumstances, energy supply would increase to more than match that of population growth as demand per capita increases. It is likely however that any future shortfall in supply will be met by further development of thermal sources. It is imperative therefore that sustainable sources of energy are more productively utilised to support growing demand.

Asia's fresh water resources and mountainous topography make an ideal location for investment into hydropower. Population and economic growth being realised in South Asia and China particularly, has increased the emphasis on exploiting the natural resources that the Himalayan region offers. Asia's reliance on hydropower as a whole has reduced through time. It is clear that hydropower generation has increased as investment and awareness of its potential has grown. Total electricity generation from all sources however has also grown exponentially as demand for energy throughout Asia has grown. Despite growing interest throughout Asia and worldwide from political leaders concerning hydropower, it is clear that its overall contribution toward total electricity generation has fallen considerably. This is the case in Pakistan, India, and China, where growing demand for power is increasingly being met by sources other than hydropower.

Nepal however is different. Since 1970 hydropower in Nepal has increased to contribute toward 99.9% of total electricity production in the region. This is due to Nepal's land locked location, its poor levels of infrastructure that restrict the movement of fossil fuels, and it's incapacity to fund overseas purchases. Despite its nearly 100% reliance on a recognised renewable energy source, Nepal's energy security can still be viewed as being vulnerable due to its sole reliance on one source of power. Nepal's vulnerability is also becoming increasingly realised due to growing concerns over evolving externalities that threaten the longevity and consistency of existing and proposed developments. Load shedding is already utilised whereby power supplies are switched off for 80 hours a week in Nepal. The need to do this is blamed on a reduction in the water levels of local rivers, extending the rolling blackouts in the country (Shrestha, 2014). Restricted scope to diversify energy supply worsens energy security concerns.

The productivity of existing hydropower stations has also reduced through time along three rivers that lie within the Himalayan region of South Asia. Hydropower development is becoming progressively less feasible due to externalities that are evolving to cause worsening efficiency concerns. River runoff and storage capacity are two variables that are becoming less reliable as local climates change. As a result, the feasibility of future projects is already at risk. Feasibility relates directly to the projects payback period. The length of time it takes a project to pay back its initial cost of development through production refers to its feasibility. This is particularly important in relation to hydropower due to the high initial start-up costs of development. Trends shown in figures 33, 34, and 35 suggest that the production figures of future projects will reduce through time, extending the pay-back period for each development. Prolonging this payback period will only add pressure to the economies of emerging countries.

The changing water quality properties of the river Sutlej have been identified due to the high density of hydropower infrastructure that it accommodates. This is very important when considering that a 1% decrease in river runoff will influence a 3% change in hydroelectric output (Laghari, 2013). River runoff reduced significantly between 1972 and 2002 (see figure 36), adding greater pressure to the significance of water storage capacity in the Himalayan region. Existing and future run of the river hydro-developments will become less productive as river discharge reduces. The timing of maximum runoff has also changed between 1972 to 2002 (see figure 37). More recently maximum runoff occurs in July rather than in June, coinciding more accurately with the Kharif growing season in South Asia. Despite this change in timing however, the reduction in maximum discharge represents a far greater concern. As runoff along the Sutlej river reduces, India and Pakistan's capacity to control and store water must develop. Precipitation surrounding the Sutlej river basin were found to have remained stationary (see figure 41). However, air temperature increased from 1901 to 2002 (see figure 40). Theory suggests that increased air temperatures translate into increased river runoff; however the data generated here contradicts this. It could therefore be argued that Collins' (2008) theory of the deglaciation discharge dividend is already being realised. A more realistic conclusion however is that growing populations in South Asia and increased river infrastructure are worsening disruptions to the natural flow of runoff.

In light of changes in river runoff, climate change, and social externalities, dam development has evolved. Since 1970 the size of dams being built has changed dramatically (see figure 45) in response to improved knowledge and environmental constraints. The number of dams being built each decade since 1900 has also changed with peak development numbers occurring during the 1970's and 1980's (see figure 42). Despite Asia having the technology and capital to develop more mega dams abundantly, hydropower developments are now smaller than they used to be. Environmental implications and social issues have made the development of mega dams more challenging as the level of opposition has increased in more recent years. As already discussed however, due to reducing river discharge levels larger scale water storage infrastructure needs to be developed if hydropower developments are to remain economically feasible. Smaller storage infrastructure will only limit the Himalayan regions ability to store water to compensate for periods of particularly low flow.

Sedimentation is already recognised throughout relevant literature as the greatest threat to hydropower productivity. Sedimentation at Tarbela Dam has seriously reduced its storage capacity and ability to produce power. Given current rates of sedimentation and river flow it is predicted that Tarbela's capacity to store water will have completely diminished by 2030 (see figure 56). Mitigation strategies are already in place to help slow the sedimentation process of Tarbela reservoir including the development of Diamer Bhasha Dam upstream of Tarbela.

The productivity of existing and future hydropower projects is under threat. Trends in current hydropower performance and the worsening implications of climate change on Himalayan river runoff are making the power source a continually less financially feasible alternative investment. Analysis of sedimentation levels and future predictions based on current trends also suggest that hydropower efficiency will be continually seriously jeopardised. Mitigation strategies must therefore be introduced to the industry if the sustainability of hydropower is to be maintained. If innovative solutions to reduced productivity are not implemented then Asia will continue to increase its reliance on thermal sources in an attempt further to meet shortfalls in supply. This in time will worsen the externalities associated with hydropower as fossil fuels act as a catalyst for climate change. Hydropower is likely to attract further investment in the future however. The huge untapped potential of the Himalayan region acts as too big an incentive to dismiss, given current shortfalls in energy and worldwide pressures over developing a greater capacity of clean power.

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